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Okayama

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(54) **OPTICAL MULTIPLEXING/DEMULTIPLEXING DEVICE**

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(73) Assignee: **Oki Electric Industry Co., Ltd.**, Tokyo (JP)

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Jun. 30, 2008	(JP)	2008-170095

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G02B 6/42 (2006.01)

(52) **U.S. Cl.** **385/39**; 385/27

(58) **Field of Classification Search** .... None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,027,686 B1 * 4/2006 Wang et al. 385/27

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JP A 8-163028 6/1996

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(74) *Attorney, Agent, or Firm*—Solaris Intellectual Property Group, PLLC

(57) **ABSTRACT**

In an optical multiplexing/demultiplexing device are arranged in parallel and disposed on a substrate. The optical multiplexing/demultiplexing device is disposed with three or more Mach-Zehnder interferometers between the first and second optical input/output ports. The optical multiplexing/demultiplexing device divides, by wavelength, multiplexed light comprising first light and second light whose wavelengths are different and which are input to one of the first optical input/output ports and outputs the multiplexed light from each of the second optical input/output ports. The absolute value of an optical path difference ΔL of each the Mach-Zehnder interferometers is constant. The optical multiplexing/demultiplexing device includes one or more each of a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes +2ΔL or −2ΔL and a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes 0.

10 Claims, 11 Drawing Sheets

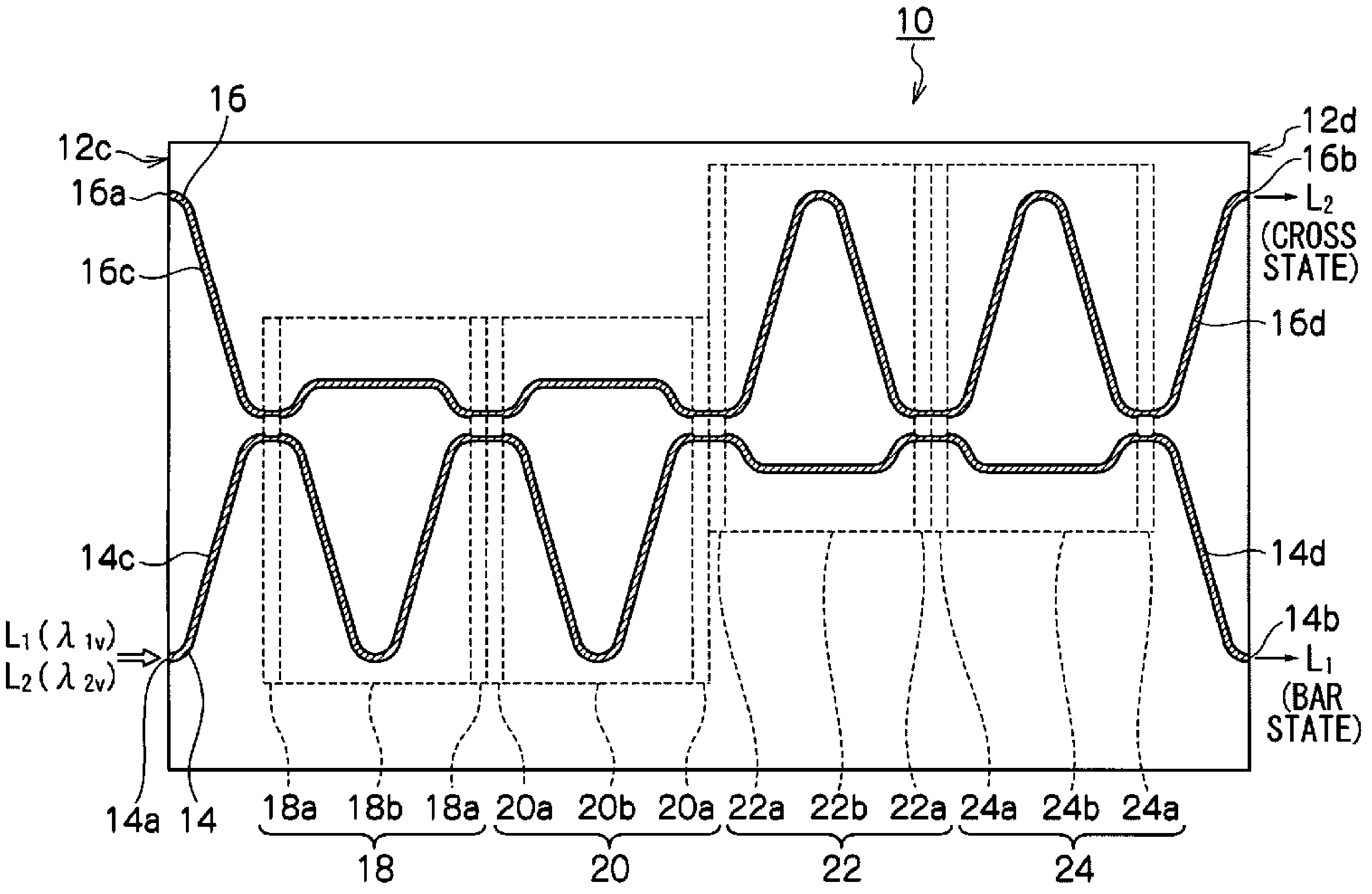


FIG. 1A

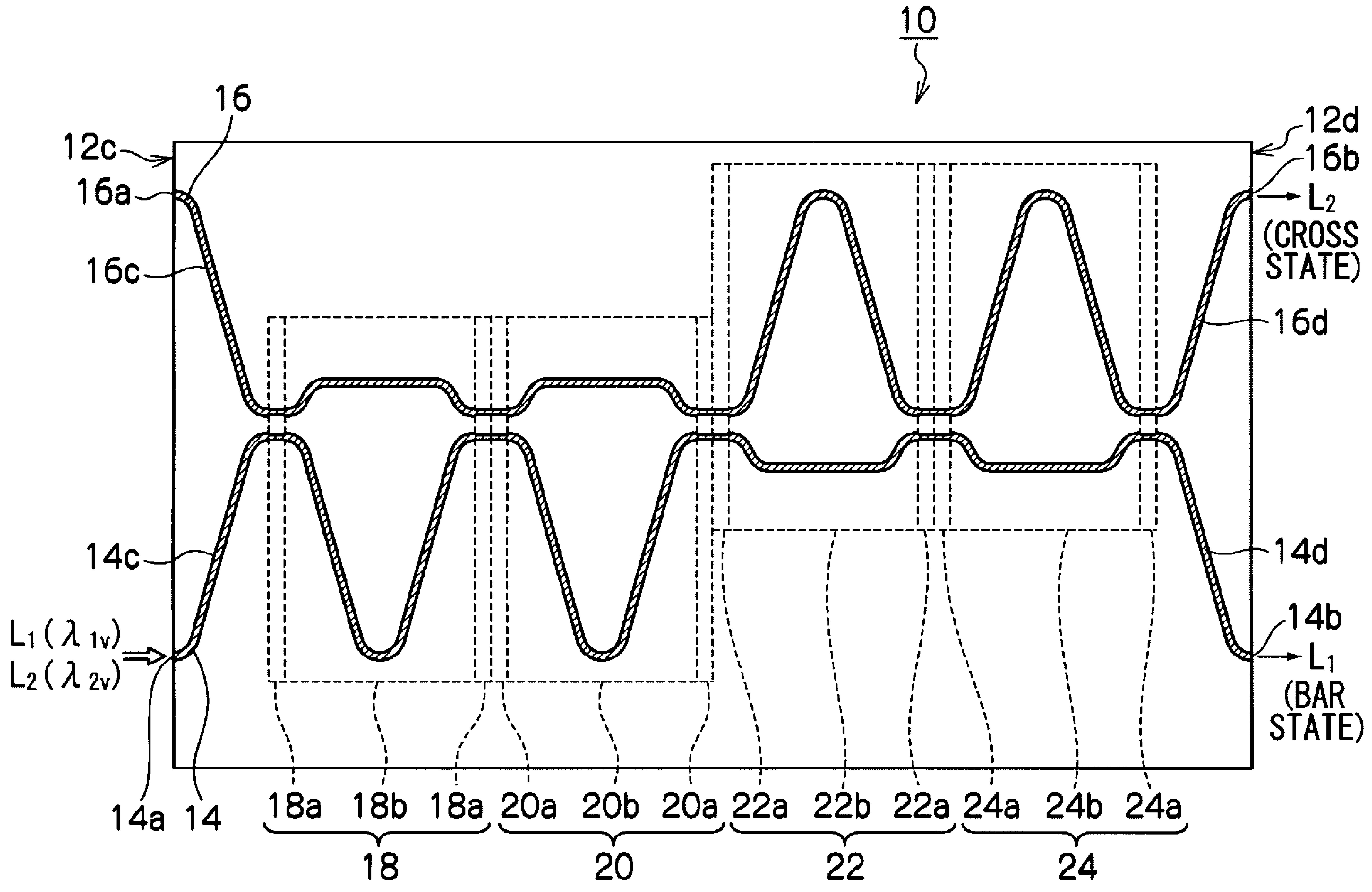

10
12c
16
16a
16c
14c
L1 (λ 1v)
L2 (λ 2v)
14a
14
18a
18b
18a
18
20a
20b
20a
20
22a
22b
22a
22
24a
24b
24a
24
12d
16b
L2 (CROSS STATE)
16d
14d
14b
L1 (BAR STATE)

FIG. 1B

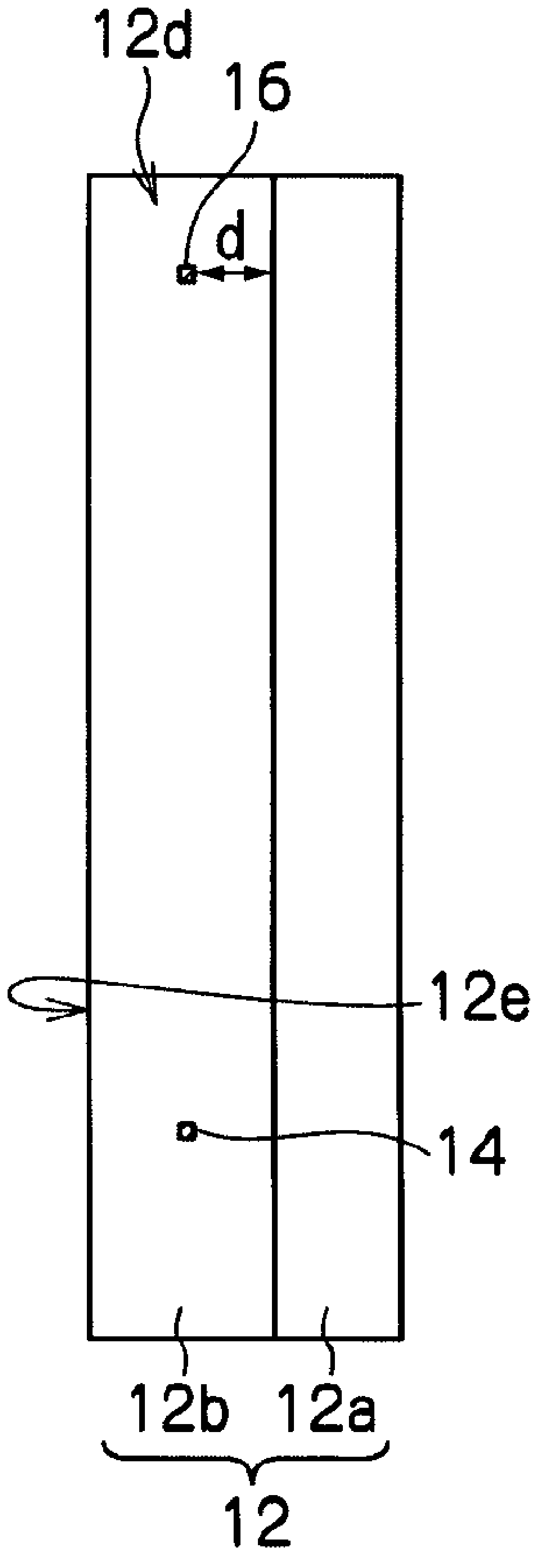

12d
16
d
12e
14
12b
12a
12

FIG. 2A

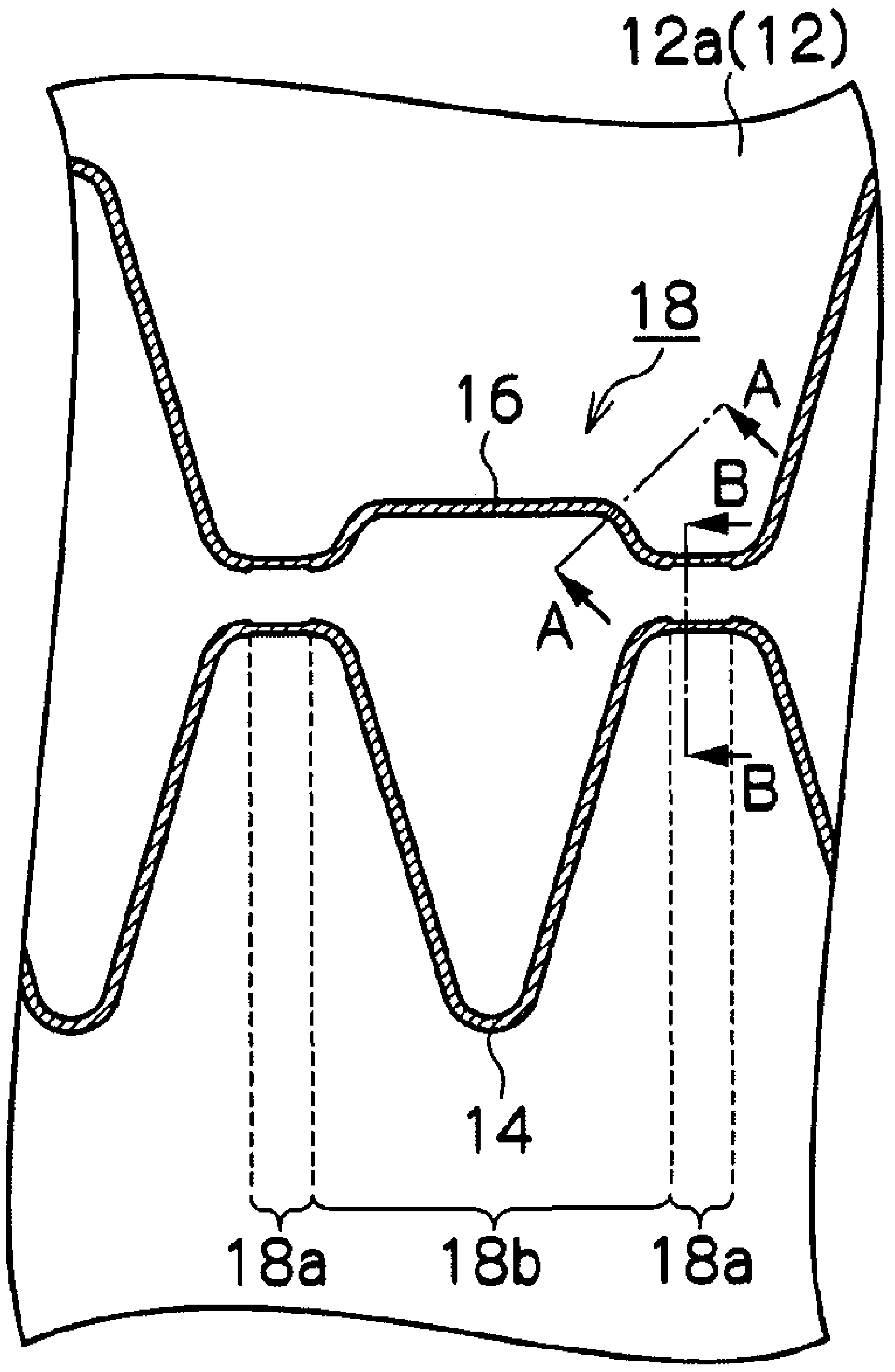


FIG. 2B

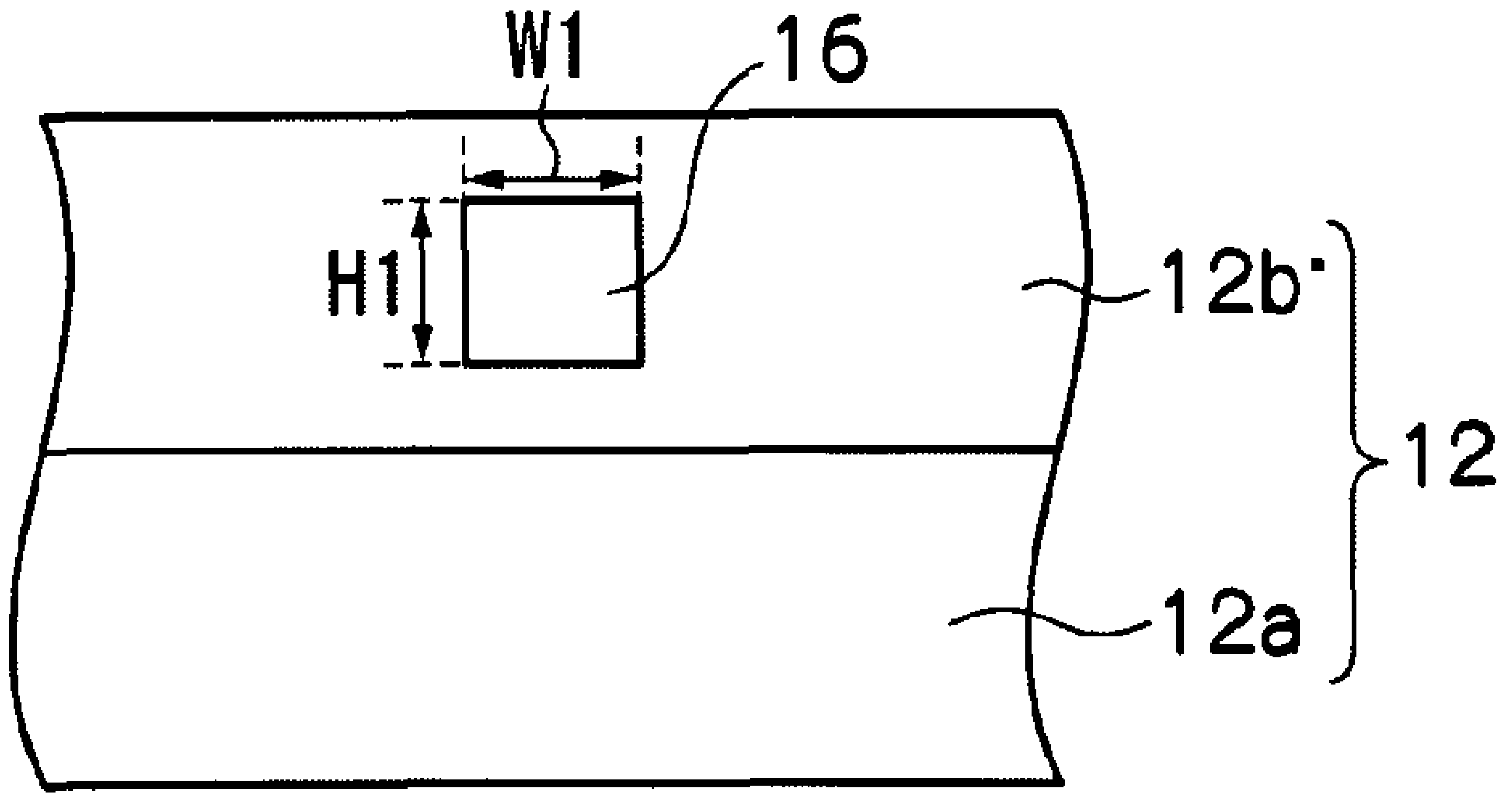


FIG. 2C

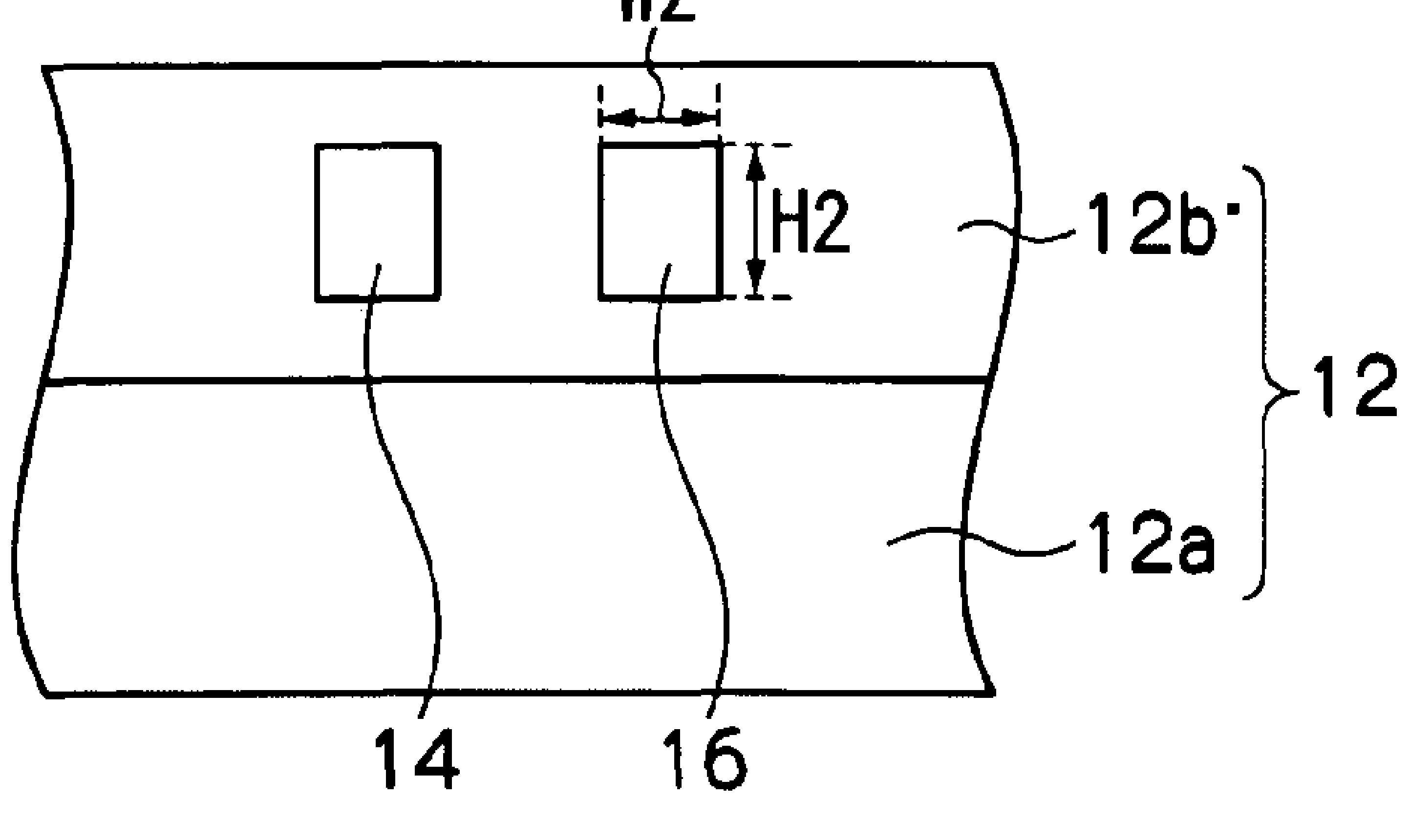


FIG. 3

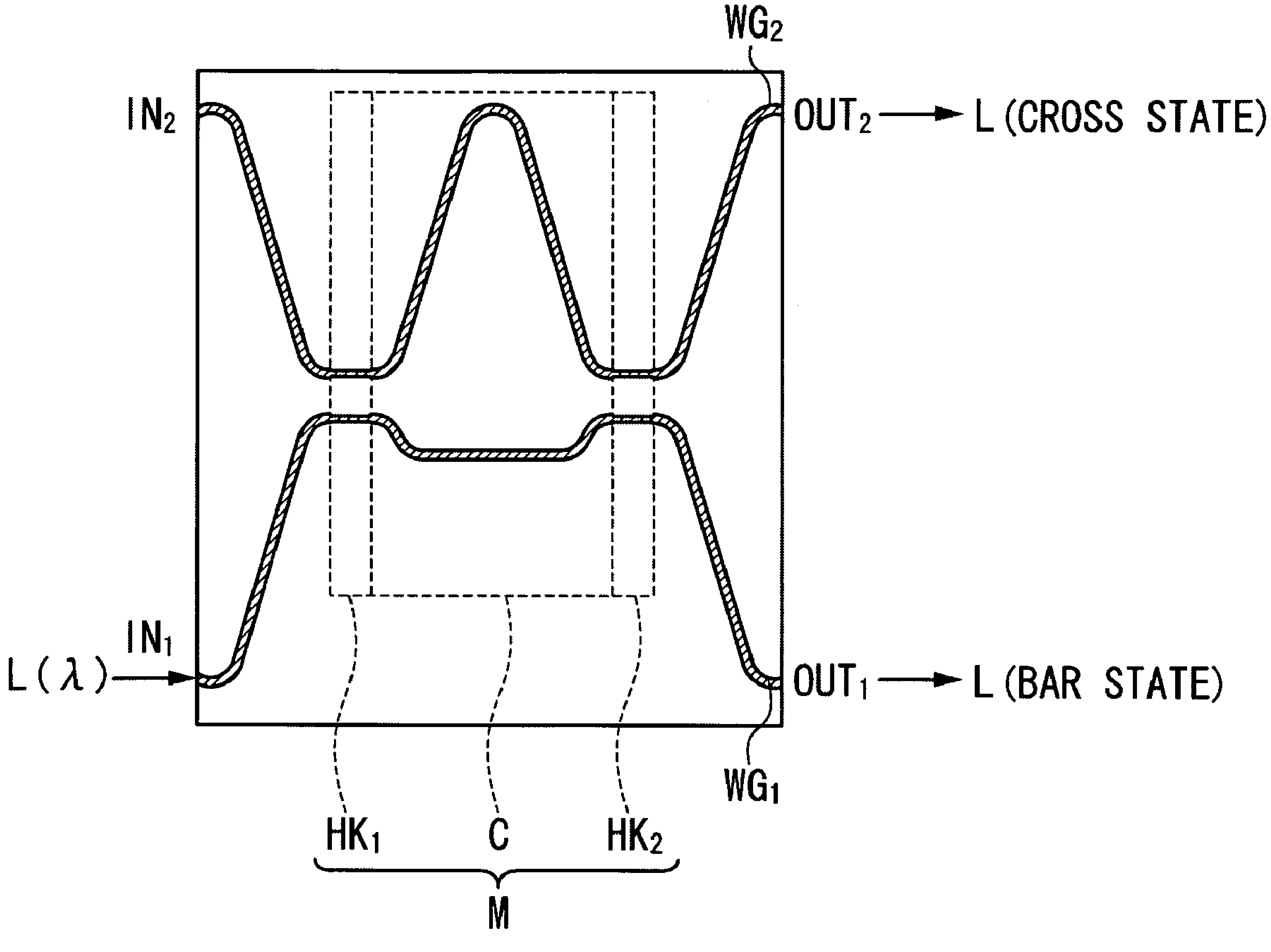

WG₂
IN₂
OUT₂ → L (CROSS STATE)
IN₁
L(λ)
OUT₁ → L (BAR STATE)
WG₁
HK₁
C
HK₂
M

FIG. 4

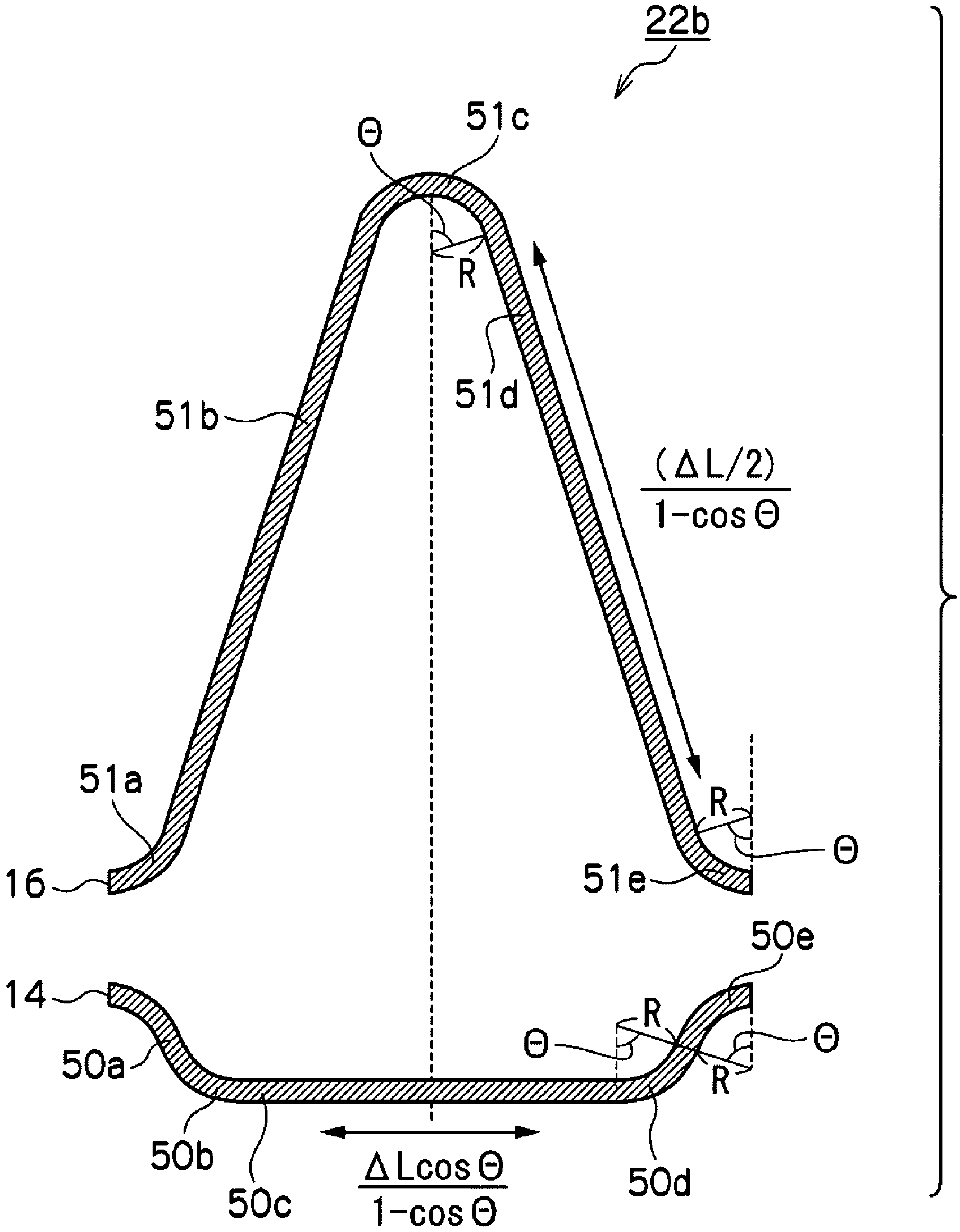

22b
Θ
51c
R
51d
51b
(ΔL/2)/(1-cos Θ)
51a
R
Θ
16
51e
50e
14
R
Θ
Θ
50a
R
50b
50c
ΔLcos Θ/(1-cos Θ)
50d

FIG. 5

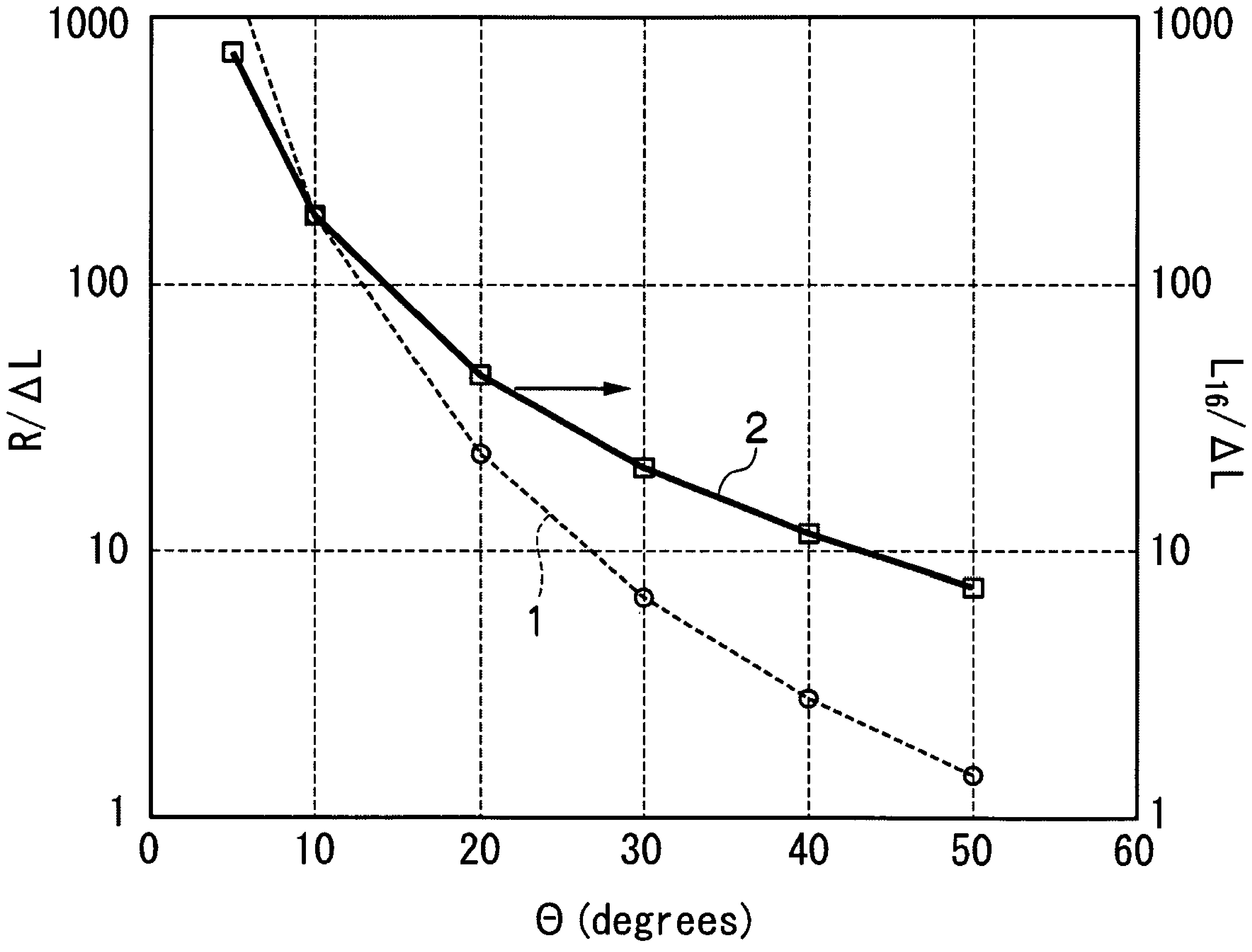

1000
100
10
1
R/ΔL
1000
100
10
1
L16/ΔL
0
10
20
30
40
50
60
Θ (degrees)
1
2

FIG. 6A

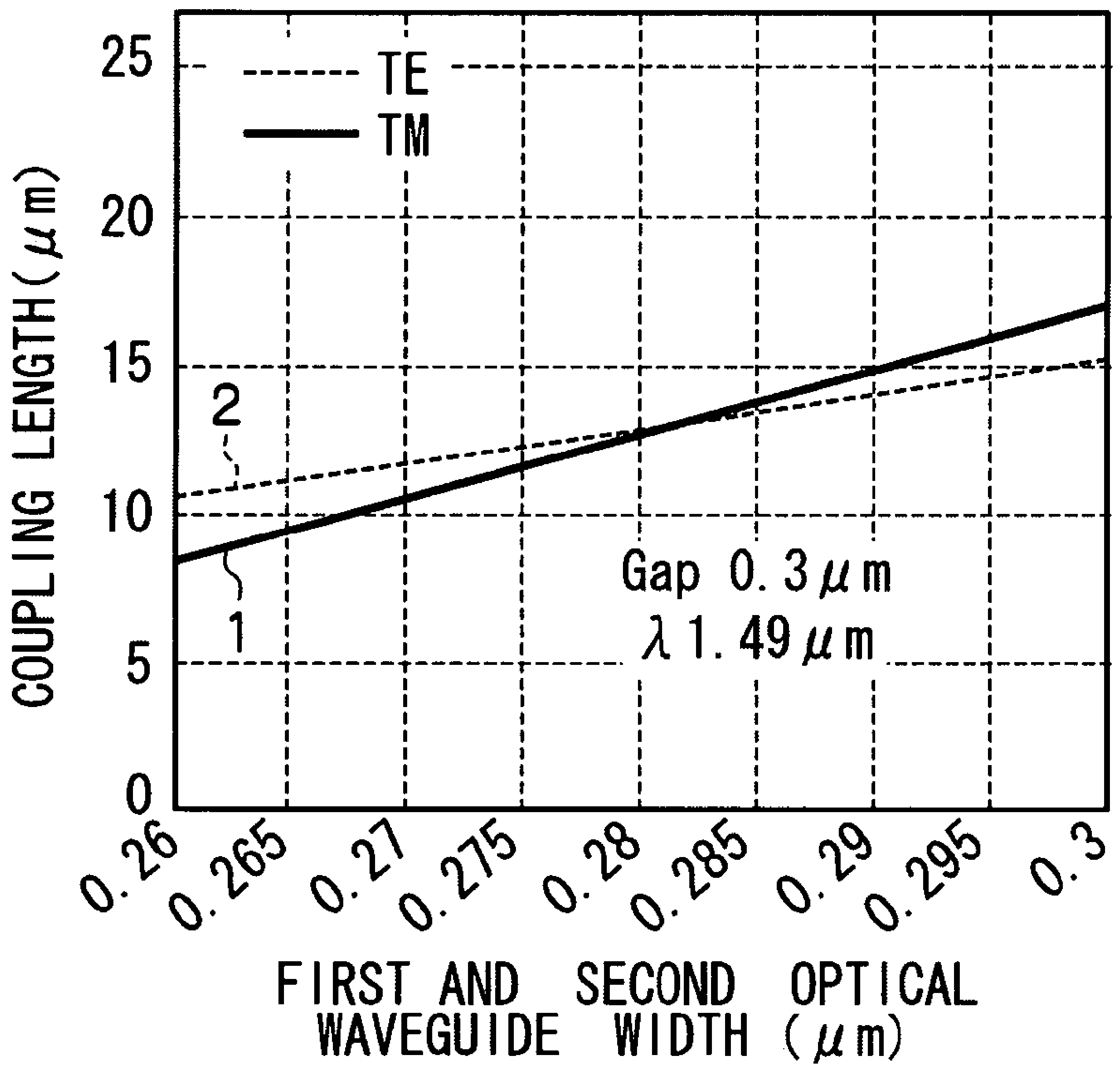

TE
TM
2
1
Gap 0.3 μm
λ 1.49 μm
COUPLING LENGTH (μm)
0
5
10
15
20
25
0.26
0.265
0.27
0.275
0.28
0.285
0.29
0.295
0.3
FIRST AND SECOND OPTICAL WAVEGUIDE WIDTH (μm)

FIG. 6B

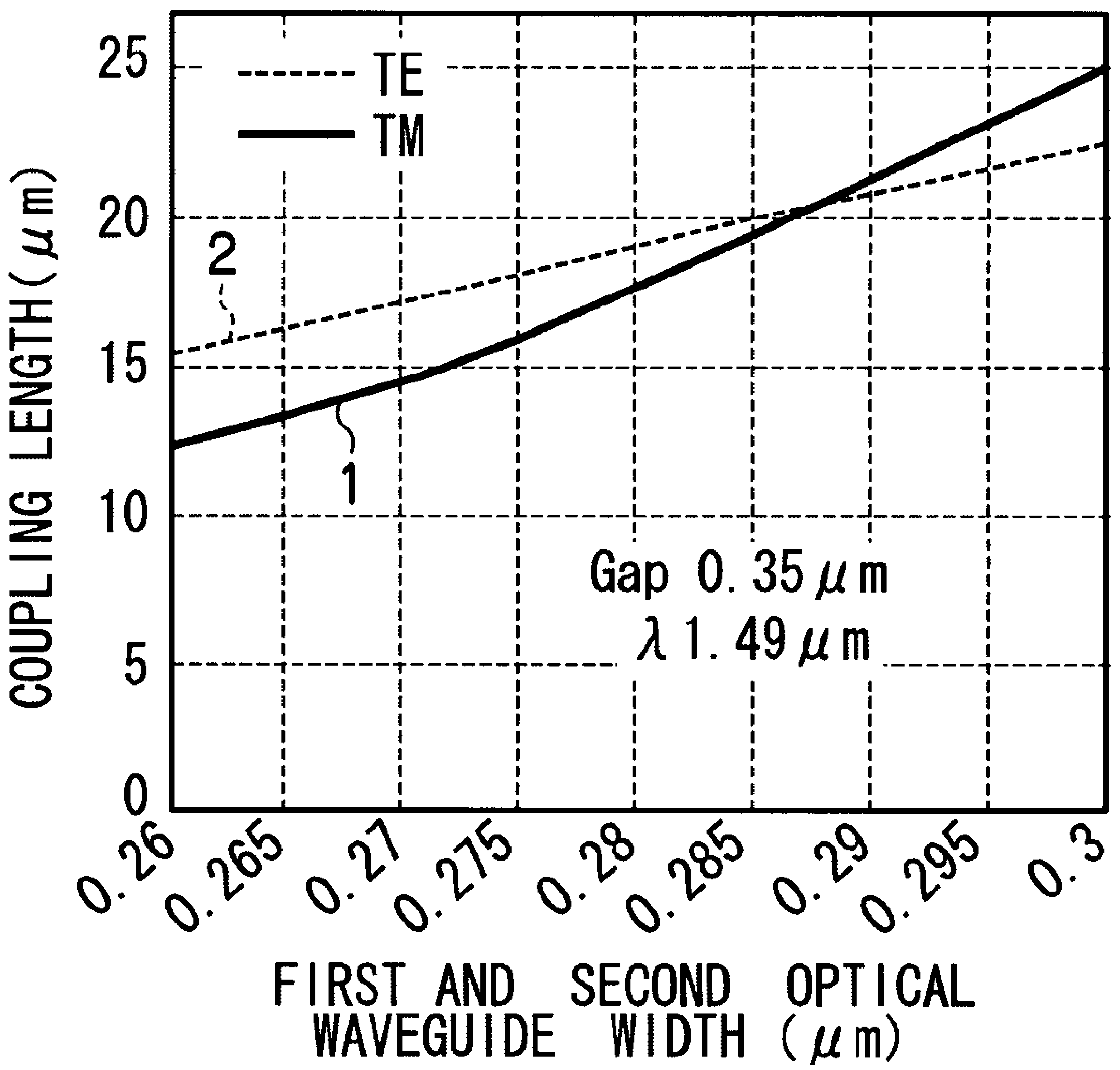

TE
TM
2
1
Gap 0.35 μm
λ 1.49 μm
COUPLING LENGTH (μm)
0
5
10
15
20
25
0.26
0.265
0.27
0.275
0.28
0.285
0.29
0.295
0.3
FIRST AND SECOND OPTICAL WAVEGUIDE WIDTH (μm)

FIG. 7

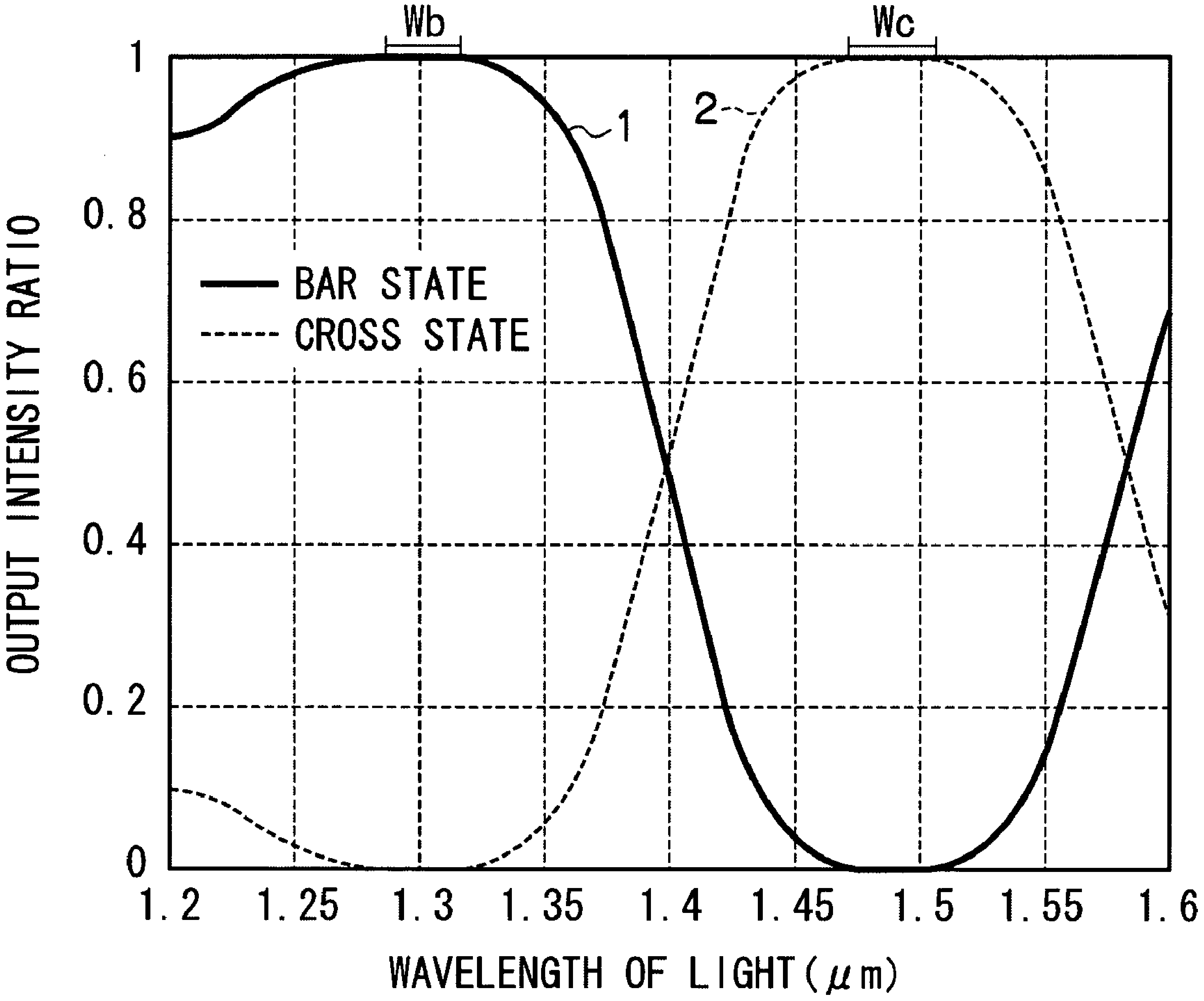

Wb
Wc
1
2
BAR STATE
CROSS STATE
OUTPUT INTENSITY RATIO
1
0. 8
0. 6
0. 4
0. 2
0
1. 2
1. 25
1. 3
1. 35
1. 4
1. 45
1. 5
1. 55
1. 6
WAVELENGTH OF LIGHT (μm)

FIG. 8A

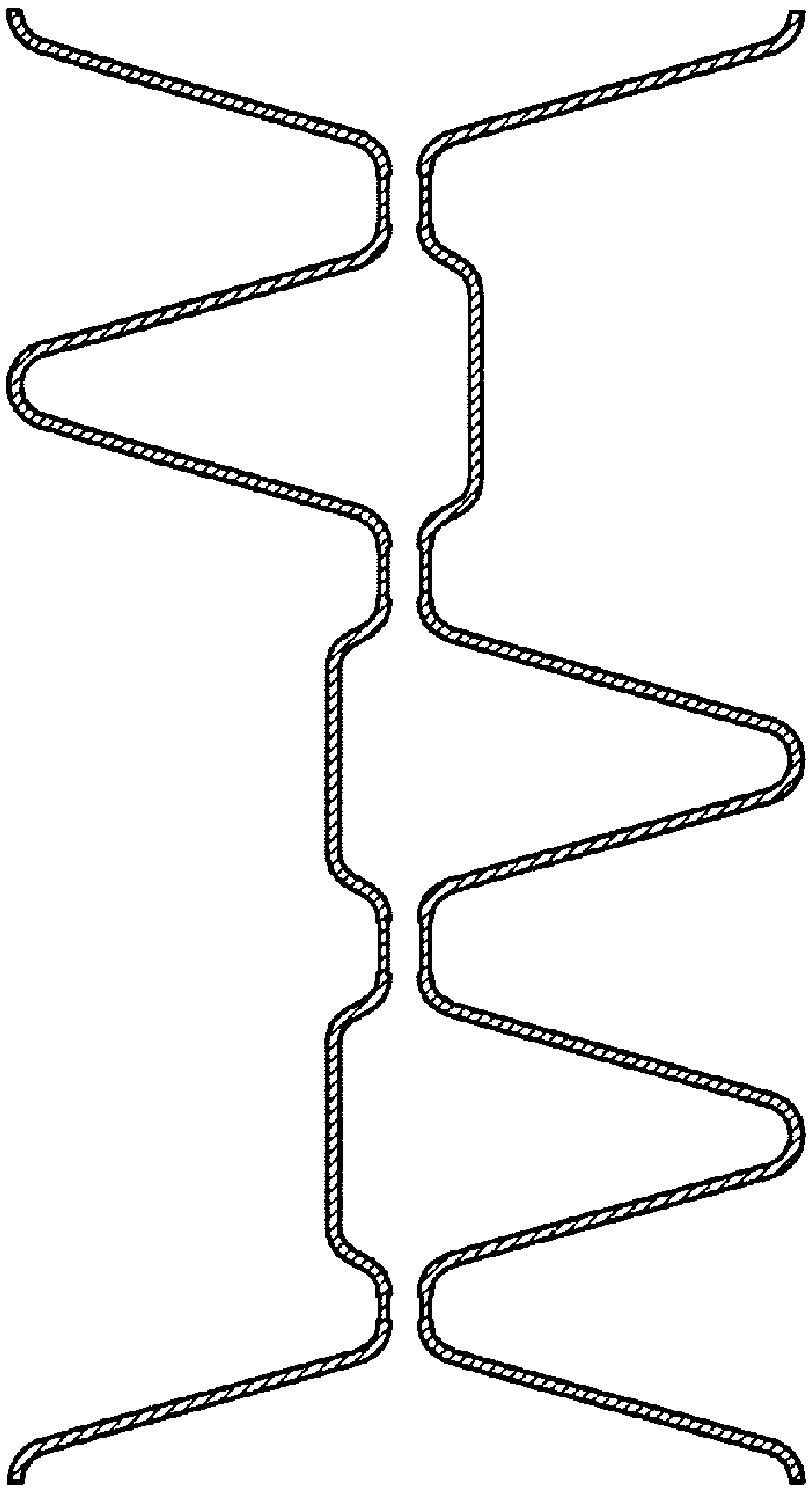


FIG. 8B

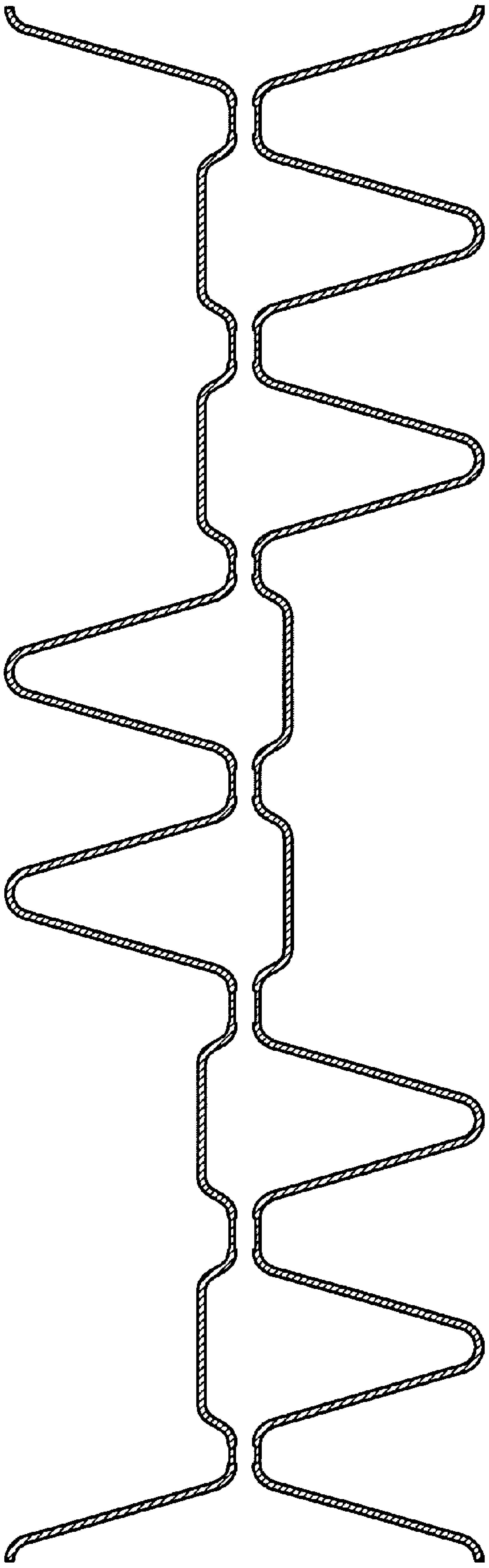


FIG. 9

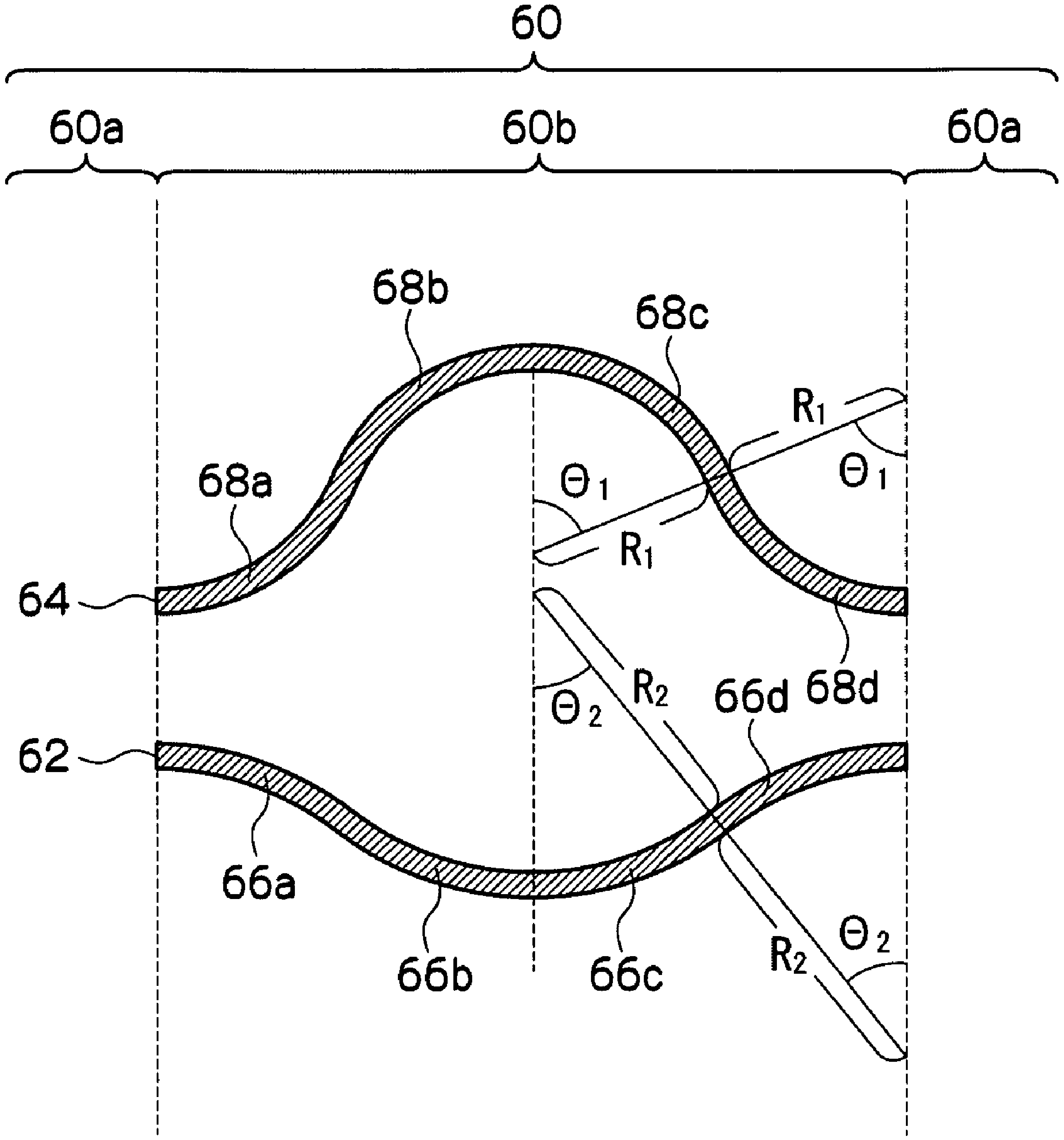

60
60a
60b
60a
68b
68c
R1
Θ1
68a
Θ1
R1
64
R2
66d
68d
Θ2
62
66a
66b
66c
R2
Θ2

FIG. 10

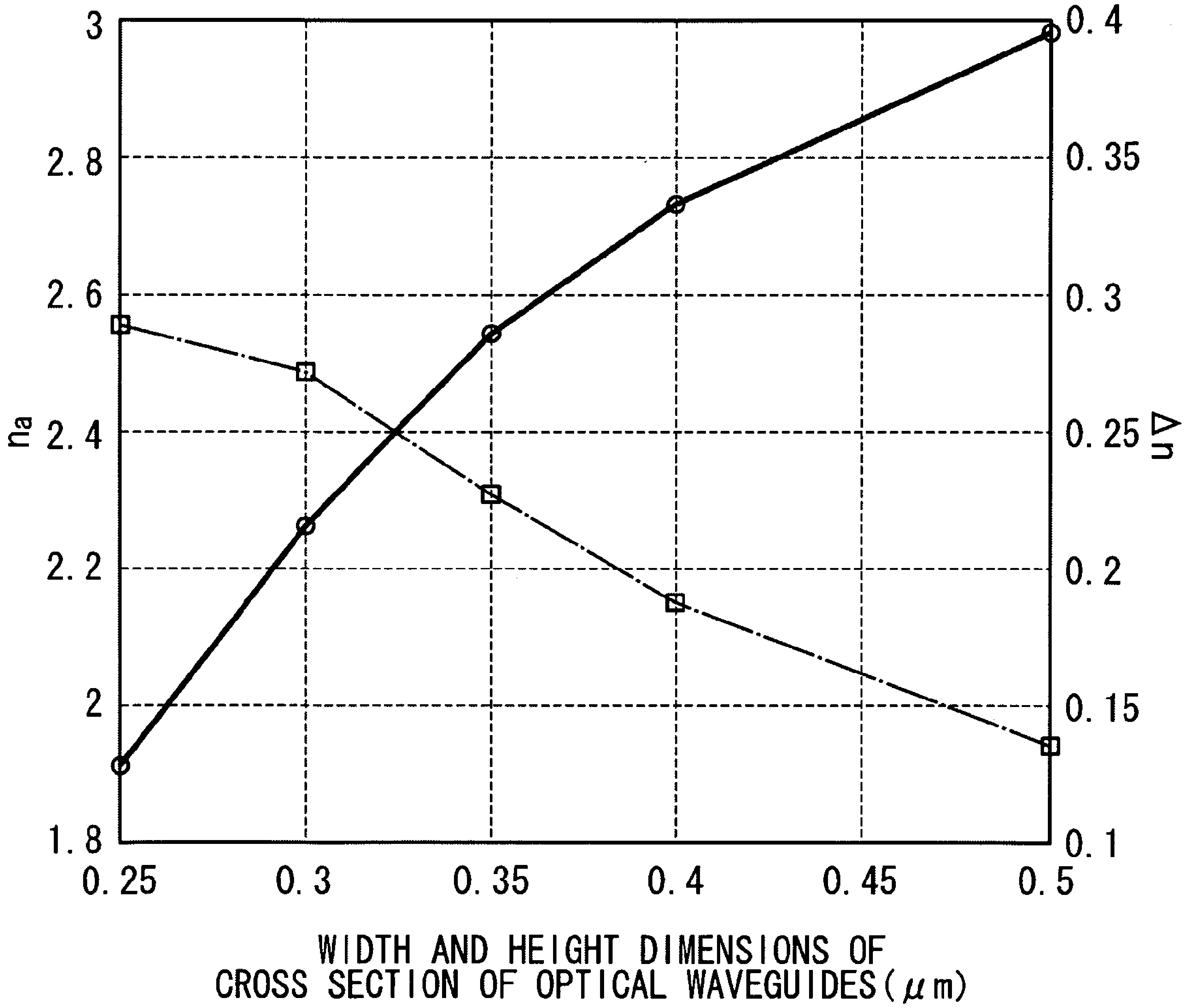
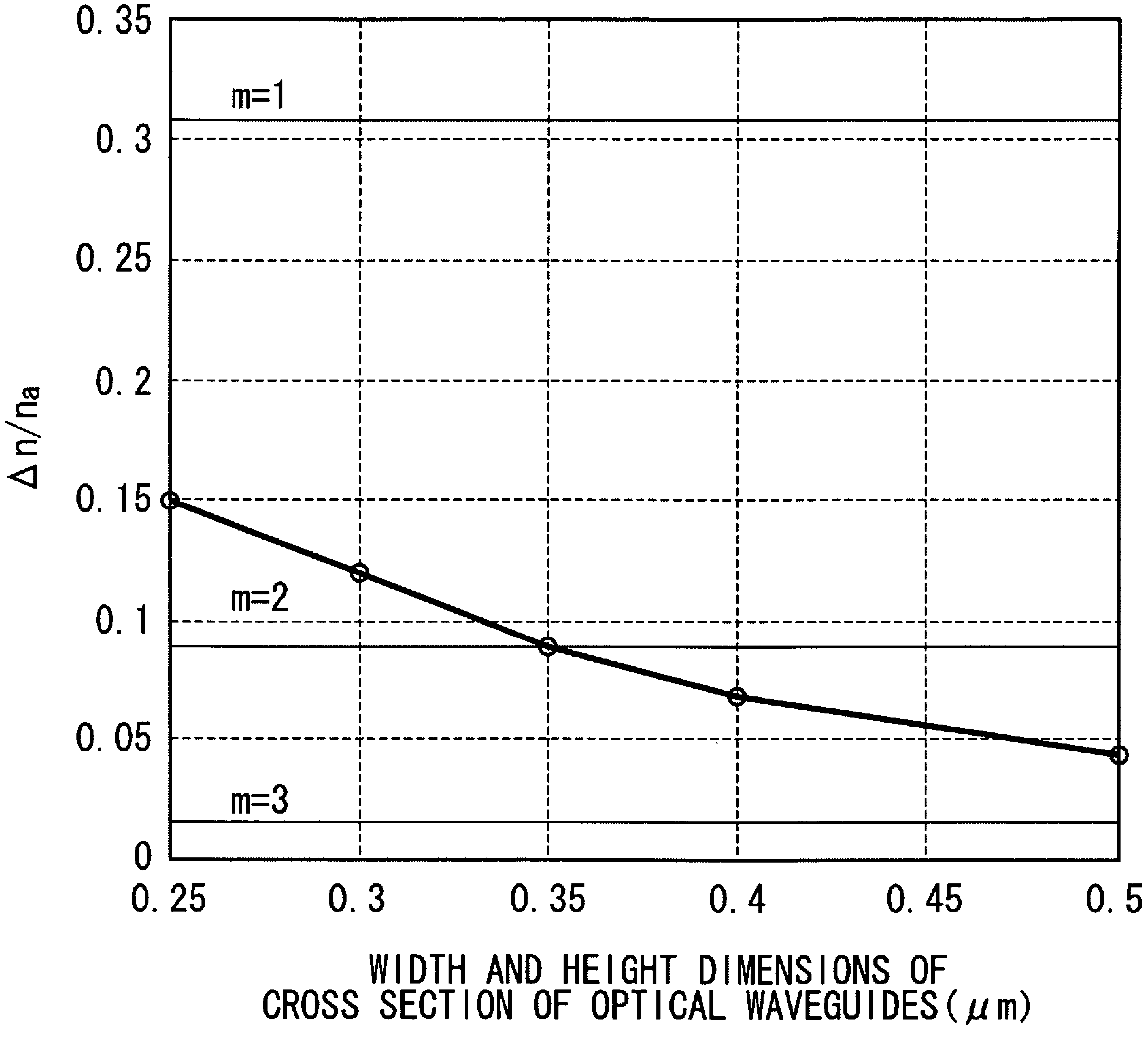

3
2. 8
2. 6
2. 4
2. 2
2
1. 8
na
0. 4
0. 35
0. 3
0. 25
0. 2
0. 15
0. 1
Δn
0. 25
0. 3
0. 35
0. 4
0. 45
0. 5
WIDTH AND HEIGHT DIMENSIONS OF
CROSS SECTION OF OPTICAL WAVEGUIDES (μm)

FIG. 11


0. 35
0. 3
0. 25
0. 2
0. 15
0. 1
0. 05
0
Δn/na
m=1
m=2
m=3
0. 25
0. 3
0. 35
0. 4
0. 45
0. 5
WIDTH AND HEIGHT DIMENSIONS OF CROSS SECTION OF OPTICAL WAVEGUIDES (μm)

OPTICAL MULTIPLEXING/DEMULTIPLEXING DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority under 35 USC 119 from Japanese Patent Application Nos. 2008-029365 and 2008-170095, the disclosures of which are incorporated by reference herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to an optical multiplexing/demultiplexing device that performs multiplexing and demultiplexing of optical signals.

2. Description of the Related Art

In an optical subscriber loop system, it is necessary to perform, by a single optical fiber, optical transmission from a subscriber to a station, that is, uplink transmission, and optical transmission from the station to the subscriber, that is, downlink transmission. For that reason, between uplink transmission and downlink transmission, lights of different wavelengths are used. Consequently, an optical multiplexing/demultiplexing device that multiplexes/demultiplexes these lights of different wavelengths becomes necessary.

The optical multiplexing/demultiplexing device that is used on the subscriber side is called an optical network unit (ONU). Many ONUs that are presently used are configured from a wavelength filter, a photodiode and a laser diode whose optical axes are spatially optically combined. Further, an ONU that renders optical axis combination unnecessary by using optical waveguides is also known (e.g., see Japanese Patent Application Laid-Open (JP-A) No. 8-163028).

Further, in recent years, an ONU that uses, as a waveguide material, Si, which has excellent mass productivity, has garnered attention. As this type of ONU, an ONU that uses a Mach-Zehnder interferometer, an ONU that uses a directional coupler, and an ONU that uses a grating are known.

However, a Si-made ONU that uses a directional coupler is susceptible to wavelength shifts of the light source. Further, the device becomes a size of the order of several hundreds of μm, so it is difficult to make the device compact.

Further, in a Si-made ONU that uses a grating, it is necessary for the period of the grating to be equal to or less than half the wavelength, so it is difficult to fabricate the device.

Moreover, in a Si-made ONU that uses a Mach-Zehnder interferometer, wavelength dependence, such as the equivalent refractive index and the coupling coefficient of the directional coupler, is extremely large, so in the wavelength range that is used by the ONU, crosstalk arises and light intensity drops, so desired characteristics have been unable to be obtained.

SUMMARY OF THE INVENTION

This invention has been made in view of the aforementioned problems. Consequently, it is an object of this invention to provide an optical multiplexing/demultiplexing device that reduces crosstalk in the wavelength range that is used by an ONU, controls intensity loss more than convention, and uses Mach-Zehnder interferometers that are capable of being made compact.

The inventors of this invention arrived at being able to achieve the aforementioned object by arranging in series

three or more Mach-Zehnder interferometers whose optical path difference ΔL is constant and by arranging the Mach-Zehnder interferometers such that there are one or more each of a pair where the sum of the optical path differences of a pair of two successive Mach-Zehnder interferometers becomes 0 and a pair where the sum of the optical path differences of a pair of two successive Mach-Zehnder interferometers becomes $+2\ \Delta L$ or $-2\ \Delta L$. That is, this invention has the following technical characteristics.

In an optical multiplexing/demultiplexing device of this invention, first and second optical waveguides, one end of each of which is configured as a first optical input/output port and the other end of each of which is configured as a second optical input/output port, are arranged in parallel and disposed on a substrate, and the optical multiplexing/demultiplexing device is disposed in series with three or more Mach-Zehnder interferometers that are formed by the first and second optical waveguides between the first and second optical input/output ports of the first and second optical waveguides.

Additionally, the optical multiplexing/demultiplexing device separates, by wavelength, multiplexed light comprising first light and second light whose wavelengths are different and which are input to one of the first optical input/output ports and outputs the multiplexed light from each of the second optical input/output ports.

In this optical multiplexing/demultiplexing device, the absolute value of an optical path difference ΔL with respect to light that propagates through the first and second optical waveguides in each of the Mach-Zehnder interferometers is constant.

Moreover, the optical multiplexing/demultiplexing device includes one or more each of a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes $+2\ \Delta L$ or $-2\ \Delta L$ and a pair of successive Mach-Zehnder interferometers where the sum of optical path differences of the interferometers becomes 0.

By setting the optical path difference ΔL of each of the Mach-Zehnder interferometers to a predetermined value using the wavelengths of the first light and the second light, the multiplexed light comprising the first light and the second light that are input to either one of the first optical input/output ports can be separated by wavelength and inputted/outputted from each of the second optical input/output ports.

Specifically, for example, when the multiplexed light comprising the first light and the second light is input to the optical multiplexing/demultiplexing device from one of the first optical input/output ports, the first light is outputted from one of the second optical input/output ports and the second light is outputted from the other of the second optical input/output ports.

Incidentally, in the first light and the second light, a reverse process is also similarly satisfied, so, for example, the first light that has been input to the optical multiplexing/demultiplexing device from one of the second optical input/output ports travels along the reverse path from what has been described above, is multiplexed with the second light, and is outputted from one of the first optical input/output ports.

That is, when the first light is an uplink signal from a subscriber to a station and the second light is a downlink signal from the station to the subscriber, this optical multiplexing/demultiplexing device can be caused to function as an ONU.

Further, when the optical path difference ΔL in one of the Mach-Zehnder interferometers is defined as (optical path length of first optical waveguide—optical path length of second optical waveguide), two types of values that are ΔL and −ΔL are calculated as the optical path difference.

Consequently, when a pair of two adjacent (successive) Mach-Zehnder interferometers is considered, three types of values that are 2 ΔL, 0 and −2 ΔL are calculated.

This optical multiplexing/demultiplexing device, is disposed with one or more of a pair of Mach-Zehnder interferometers where the sum of their optical path differences becomes 2 ΔL or −2 ΔL and is disposed with one or more of a pair of Mach-Zehnder interferometers where the sum of their optical path differences becomes 0.

By configuring the optical multiplexing/demultiplexing device in this manner, the wavelength band of light (second light) that is inputted/outputted in a cross state to/from the Mach-Zehnder interferometers and the wavelength band of light (first light) that is inputted/outputted in a bar state can be broadened.

In this optical multiplexing/demultiplexing device, when λ_1 and λ_2 ($\lambda_2>\lambda_1$) respectively represent the wavelengths of the first light and the second light inside the first and second optical waveguides, it is preferred that ΔL is given by the following expressions.

$$\Delta L=(2m+1)\times\lambda_1 \text{ and } \Delta L=2m\times\lambda_2 \text{ (where m is a natural number)} \quad (1)$$

By configuring the optical multiplexing/demultiplexing device in this manner, the first light of wavelength λ_1 propagates through the optical multiplexing/demultiplexing device in a bar state. Further, the second light of wavelength λ_2 ($\lambda_2>\lambda_1$) propagates through the optical multiplexing/demultiplexing device in a cross state. As a result, the optical multiplexing/demultiplexing device can separate the wavelengths of the first light and the second light.

In this optical multiplexing/demultiplexing device, it is preferred that the first light is outputted in a bar state from one of the second optical input/output ports and that the second light is outputted in a cross state from the other of the second optical input/output ports.

In this optical multiplexing/demultiplexing device, it is preferred that first and second optical waveguides are formed using Si as a material.

By configuring the optical multiplexing/demultiplexing device in this manner, the optical multiplexing/demultiplexing device can be manufactured easily utilizing a Si semiconductor device manufacturing process.

In this optical multiplexing/demultiplexing device, it is preferred that cross-sectional shapes, orthogonal to the light propagation direction, of the first and second optical waveguides that configure bend waveguide sections of the Mach-Zehnder interferometers are square, and that cross-sectional shapes, orthogonal to the light propagation direction, of the first and second optical waveguides that configure directional coupler sections of the Mach-Zehnder interferometers are rectangular where the length in a direction perpendicular to a main surface of the substrate is longer than the length in a direction parallel to the main surface of the substrate.

By configuring the optical multiplexing/demultiplexing device in this manner, it can be ensured that the optical multiplexing/demultiplexing device is not dependent on polarization.

In this optical multiplexing/demultiplexing device, it is preferred that the bend waveguide sections are formed by a straight waveguide and by a plurality of curve waveguides whose radii of curvature are equal.

By configuring the optical multiplexing/demultiplexing device in this manner, loss of the first light and the second light in the optical multiplexing/demultiplexing device can be reduced even more.

In the aforementioned optical multiplexing/demultiplexing device, it is preferred that the optical path difference ΔL is determined utilizing the wavelength dependence of the equivalent refractive index of the material that configures the first and second optical waveguides.

In the aforementioned optical multiplexing/demultiplexing device, it is preferred that the material that configures the first and second optical waveguides is Si.

In the aforementioned optical multiplexing/demultiplexing device, it is preferred that, when Δλ represents the wavelength difference between the first light and the second light, Δn represents the equivalent refractive index difference between the first and second optical waveguides that the first light and the second light experience, and m is a positive integer, the following expression (15) is satisfied and the optical path difference ΔL satisfies the following expression (16).

$$\Delta n/n_2=(1-\Delta\lambda/\lambda_2)/(2m)-\Delta\lambda/\lambda_2 \quad (15)$$

$$2n_2\Delta L/\lambda_2=(1-\Delta\lambda/\lambda_2)/(\Delta\lambda/\lambda_2+\Delta n/n_2) \quad (16)$$

Here, n_2 is the equivalent refractive index of an optical waveguide that the second light experiences.

In another optical multiplexing/demultiplexing device pertaining to this invention, first and second optical waveguides, one end of each of which is configured as a first optical input/output port and the other end of each of which is configured as a second optical input/output port, are arranged in parallel and disposed on a substrate, and the optical multiplexing/demultiplexing device is disposed in series with three or more Mach-Zehnder interferometers that are formed by the first and second optical waveguides between the first and second optical input/output ports of the first and second optical waveguides.

Additionally, the optical multiplexing/demultiplexing device separates, by wavelength, multiplexed light of N wavelengths (where N is an integer such that $N\geqq3$) whose wavelengths are different and which are input to either one of the first optical input/output ports, outputs light of (N−i) wavelength (where i is an integer such that $1\leqq i\leqq N-1$) from the second optical input/output port of the first optical waveguide, and outputs light of i wavelength is outputted from the second optical input/output port of the second optical waveguide.

Here, when m is an integer equal to or greater than 1, the absolute value of an optical path difference ΔL with respect to light that propagates through the first and second optical waveguides in each of the Mach-Zehnder interferometers is constant

Moreover, the optical multiplexing/demultiplexing device includes one or more each of a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes +2 ΔL or −2 ΔL and a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes 0.

Further still, the following expression (15)' and expression (16)' are simultaneously satisfied.

$$\Delta n/n_a=\Delta m(-\Delta\lambda/\lambda_a)/(2m)-\Delta\lambda/\lambda_a \quad (15)'$$

$$2n_a\Delta L/\lambda_a=2m=\Delta m(1-\Delta\lambda/\lambda_a)/(\Delta\lambda/\lambda_a+\Delta n/n_a) \quad (16)'$$

Δm is an integer that is given by 2−N, λ_a is a reference wavelength, and n_a is the equivalent refractive index of an optical waveguide that light of the reference wavelength experiences.

This invention has the aforementioned technical characteristics. Thus, there is obtained an optical multiplexing/demultiplexing device that reduces crosstalk in the wavelength range that is used by an ONU, controls intensity loss more than convention, and uses Mach-Zehnder interferometers that are capable of being made compact.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred exemplary embodiment of the present invention will be described in detail based on the following figures, wherein:

FIG. **1**A is a plan diagram of an optical multiplexing/demultiplexing device of this exemplary embodiment;

FIG. **1**B is a side diagram of the optical multiplexing/demultiplexing device of this exemplary embodiment;

FIG. **2**A is a plan diagram of a Mach-Zehnder interferometer;

FIG. **2**B is a cut end surface diagram of a cut surface along line A-A of FIG. **2**A;

FIG. **2**C is a cut end surface diagram of a cut surface along line B-B of FIG. **2**A;

FIG. **3** is a plan diagram schematically showing the structure of a Mach-Zehnder interferometer;

FIG. **4** is an enlarged plan diagram of relevant portions of a bend waveguide section;

FIG. **5** is a diagram showing the relationship between R/ΔL and θ and the relationship between $L_{16}/\Delta L$ and θ;

FIG. **6**A is a simulation result showing the relationship between coupling lengths and first and second optical waveguide widths for making directional coupler sections polarization-independent;

FIG. **6**B is a simulation result showing the relationship between coupling lengths and first and second optical waveguide widths for making directional coupler sections polarization-independent;

FIG. **7** is a diagram provided for describing operating characteristics of the optical multiplexing/demultiplexing device of this exemplary embodiment;

FIG. **8**A is a diagram showing a modification of the optical multiplexing/demultiplexing device;

FIG. **8**B is a diagram showing a modification of the optical multiplexing/demultiplexing device;

FIG. **9** is a diagram provided for describing a modification of the optical multiplexing/demultiplexing device;

FIG. **10** is a simulation result for determining Δn and n_a; and

FIG. **11** is a characteristic diagram where expression (15) is graphed.

DETAILED DESCRIPTION OF THE INVENTION

Below, an exemplary embodiment of this invention will be described. It will be noted that each drawing only generally shows the shape, size and the arrangement relationship of each component to the extent that this invention can be understood. Further, below, a preferred configural example of this invention will be described, but the material and numerical condition of each component are simply preferred examples. Consequently, this invention is not limited in any way to the exemplary embodiment below. Further, in each of the drawings, identical reference numerals are given to common components, and sometimes description thereof will be omitted.

(Structure)

The structure of an optical multiplexing/demultiplexing device **10** of this exemplary embodiment will be described with reference to FIG. **1**A to FIG. **9**. FIG. **1**A is a plan diagram of the optical multiplexing/demultiplexing device **10**. FIG. **1**B is a side diagram of the optical multiplexing/demultiplexing device **10**. It will be noted that, in FIG. **1**A and FIG. **1**B, diagonal lines are administered to regions that represent first and second optical waveguides **14** and **16** taking in consideration the ease of understanding the drawings.

Referring to FIG. **1**A, the optical multiplexing/demultiplexing device **10** is formed by a substrate **12** and first and second optical waveguides **14** and **16**. The substrate **12** is configured in a rectangular parallelepiped shape, for example, from a bottom layer **12***a* whose material is single crystal silicon and a top layer **12***b* that serves as a clad whose material is a silicon oxide film. Additionally, in the top layer **12***b*, the first optical waveguide **14** and the second optical waveguide **16** that serve as cores whose material is single crystal silicon are arranged in parallel and disposed.

The first and second optical waveguides **14** and **16** are disposed in positions where their depths measured in a thickness direction from a flat first main surface **12***e* of the substrate **12** are equal. Further, a distance d between the bottom layer **12***a* and the first and second optical waveguides **14** and **16** is ordinarily configured to be equal to or greater than 1 μm in order to prevent light leakage to the bottom layer **12***a*.

The first optical waveguide **14** is disposed with a first optical input/output port **14***a* in one side surface **12***c* of the substrate **12**. The first optical waveguide **14** is also disposed with a second optical input/output port **14***b* in another side surface **12***d* of the substrate **12**.

Similarly, the second optical waveguide **16** is disposed with a first optical input/output port **16***a* in the one side surface **12***c* of the substrate **12**. The second optical waveguide **16** is also disposed with a second optical input/output port **16***b* in the other side surface **12***d* of the substrate **12**.

In this exemplary embodiment, as one example, between the first optical input/output ports **14***a* and **16***a* and the second optical input/output ports **14***b* and **16***b*, four Mach-Zehnder interferometers **18**, **20**, **22** and **24** that are formed by the first and second optical waveguides **14** and **16** are formed in series.

The details of the Mach-Zehnder interferometers **18** to **24** will be described later with reference to FIG. **2**A, but the Mach-Zehnder interferometers **18** to **24** are arranged in the order of **18**, **20**, **22** and **24** from the side of the first optical input/output ports **14***a* and **16***a* toward the second optical input/output ports **14***b* and **16***b*.

Additionally, the Mach-Zehnder interferometer **18** and the first optical input/output ports **14***a* and **16***a* are interconnected by connection-use optical waveguides **14***c* and **16***c*. Similarly, the Mach-Zehnder interferometer **24** and the second optical input/output ports **14***b* and **16***b* are interconnected by connection-use optical waveguides **14***d* and **16***d*.

The structures of the Mach-Zehnder interferometers **18** to **24** are the same except with regard to which of the first optical waveguide **14** and second optical waveguide **16** is longer in later-described bend waveguide sections **18***b* to **24***b*.

In the example shown in FIG. **1**A, in the Mach-Zehnder interferometers **18** and **20**, the optical path length of the first optical waveguide **14** is formed longer than the optical path length of the second optical waveguide **16**, and in the Mach-Zehnder interferometers **22** and **24**, the optical path length of the second optical waveguide **16** is formed longer than the optical path length of the first optical waveguide **14**. The first and second optical waveguides **14** and **16** respectively include straight waveguide regions that form directional couplers along a straight direction from the first optical input/output ports **14***a* and **16***a* to the second optical input/output ports **14***b* and **16***b*. Moreover, ending point positions in the straight direction from the straight waveguide regions on the front side of the first and second optical waveguides **14** and **16** to bend waveguide regions are the same positions. Further, straight direction starting point positions from the bend waveguide regions of the first and second optical waveguides **14** and **16** to the straight waveguide regions on the rear side are the same positions. Consequently, in relation to each of the Mach-Zehnder interferometers **18** to **24**, ΔL represents an optical path difference between the first and second optical waveguides **14** and **16** in the bend waveguide sections **18***b* to **24***b*, that is, "(optical path length of first optical waveguide **14**)−(optical path length of second optical waveguide **16**)". In this case, the absolute value of ΔL is constant regardless of the Mach-Zehnder interferometers **18** to **24**. That is, in the bend waveguide sections **18***b* to **24***b*, the optical path differences between the first optical waveguide **14** and the second optical waveguide **16** are equal regarding all of the Mach-Zehnder interferometers **18** to **24**. It will be noted that all of the regions of the bend waveguide sections **18***b* to **24***b* may be formed by bend regions, or they may be partially partitioned into bend regions and straight regions and formed. How the bend waveguide sections **18***b* to **24***b* are to be configured is a design problem.

Further, this optical multiplexing/demultiplexing device **10** is disposed with one or more each of a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes +2 ΔL or −2 ΔL and a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes 0. In the example shown in FIG. **1**A, the former pair is the Mach-Zehnder interferometers **18** and **20** and **22** and **24**, and the latter pair is the Mach-Zehnder interferometers **20** and **22**.

The sum of the optical path differences in the pairs (**18** and **20**, **20** and **22**, **22** and **24**) of two successive Mach-Zehnder interferometers is determined. Thus, in pair **18** and **20**, the sum of the optical path differences becomes 2 ΔL (=ΔL+ΔL). In pair **20** and **22**, the sum of the optical path differences becomes 0 (=ΔL+(−ΔL)). Further, in pair **22** and **24**, the sum of the optical path differences becomes −2 ΔL (=(−ΔL)+(−ΔL)). In other words, this optical multiplexing/demultiplexing device **10** is disposed with two pairs (**18** and **20**, **22** and **24**) of Mach-Zehnder interferometers where the sum of their optical path differences becomes +2 ΔL or −2 ΔL and is disposed with one pair (**20** and **22**) of Mach-Zehnder interferometers where the sum of their optical path differences becomes 0.

The reason why the optical multiplexing/demultiplexing device **10** is disposed with one of more each of a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes +2 ΔL or −2 ΔL (below, also called a "bar state pair") and a pair of two successive Mach-Zehnder interferometers where the sum of their optical path differences becomes 0 (below, also called a "cross state pair") will be described below with reference to FIG. **7**.

The inventors performed a simulation where the total number of pairs of the bar state pair and the cross state pair was made constant and where the number of the bar state pair was increased and reduced. As a result, it became apparent that the more the number of the bar state pair increases, the more the wavelength band of the bar state, in other words, a width Wb of a flat portion of a peak of curve **1** in FIG. **7**, becomes wider.

It also became apparent that the more the number of the cross state pair increases, the more the wavelength band of the cross state, in other words, a width of a flat portion Wc of a peak of curve **2** in FIG. **7**, becomes wider.

Because of these facts, the wavelength bands of the bar state and the cross state can be broadened to an extent that can be practically allowed as a result of the optical multiplexing/demultiplexing device **10** being disposed with at least one or more each of the bar state pair and the cross state pair.

(Structure of the Mach-Zehnder Interferometers)

Next, referring to FIG. **2**A to FIG. **2**C, the structure of the Mach-Zehnder interferometers will be described in detail using the Mach-Zehnder interferometer **18** as an example. FIG. **2**A is a plan diagram showing the waveguide structure of the Mach-Zehnder interferometer **18** excluding the top layer **12***b* of the substrate **12**. FIG. **2**B is a cut end surface diagram of a cut surface along line A-A of FIG. **2**A. FIG. **2**C is a cut end surface diagram of a cut surface along line B-B of FIG. **2**A.

Referring to FIG. **2**A, the Mach-Zehnder interferometer **18** is disposed with directional coupler sections **18***a* and **18***a* and the bend waveguide section **18***b*.

The directional coupler sections **18***a* and **18***a* of the first and second optical waveguides **14** and **16** are sections that combine to form directional couplers, and these sections **18***a* and **18***a* are sections where the first and second optical waveguides **14** and **16** are arranged in parallel at a gap capable of optical coupling.

The bend waveguide section **18***b* is a region between the directional coupler sections **18***a* and **18***a* and, as has already been described, is formed by combining a bend region where the first and second optical waveguides **14** and **16** of different lengths are curved into a predetermined shape and straight regions. In the Mach-Zehnder interferometers **18** and **20**, the optical path length of the first optical waveguide **14** is formed longer than the optical path length of the second optical waveguide **16** (see FIG. **1**A).

It will be noted that the optical path difference ΔL between the first and second optical waveguides **14** and **16** in the bend waveguide section **18***b* and a design of the bend waveguide section **18***b* that achieves ΔL will be described later.

Further, referring to FIG. **2**B and FIG. **2**C, it will be understood that, in the directional coupler sections **18***a* and the bend waveguide section **18***b*, the heights of the first and second optical waveguides **14** and **16**, that is, their lengths at a right angle to the light propagation direction and perpendicular to the main surface **12***e* of the substrate **12**, are equal, but the widths of the first and second optical waveguides **14** and **16**, that is, their lengths at a right angle to the light propagation direction and parallel to the main surface **12***e* of the substrate **12**, are different.

Further, in the bend waveguide section **18***b*, transverse cross-sectional shapes of the first and second optical waveguides **14** and **16** that are obtained by cutting in a plane perpendicular to the light propagation direction are square (see FIG. **2**B). In other words, a width **W1** and a height **H1** are equal.

In contrast, in the directional coupler sections **18***a*, transverse cross-sectional shapes of the first and second optical waveguides **14** and **16** are rectangular where the width is narrower than in the bend waveguide section **18***b*, so the height **H1** is larger than a width **W2**.

Consequently, at the boundary portions between the bend waveguide section **18***b* and the directional coupler sections **18***a*, the widths of the first and second optical waveguides **14** and **16** change discontinuously.

It will be noted that the difference in the widths of the optical waveguides in the directional coupler sections **18***a* and the bend waveguide section **18***b* will be described later.

(Regarding ΔL)

Next, the optical path difference ΔL between the first and second optical waveguides **14** and **16** in the bend waveguide sections **18***b* to **24***b* of the Mach-Zehnder interferometers **18** to **24** will be described.

ΔL is determined in consideration of the wavelength of light that the optical multiplexing/demultiplexing device **10** is to multiplex/demultiplex. Usually, in a Mach-Zehnder interferometer, the optical path difference in the bend waveguide section is appropriately set with respect to the wavelength of light that has been input, whereby the input light can be outputted in either a bar state or a cross state.

The bar state and the cross state will be more specifically described with reference to FIG. **3**. FIG. **3** is a plan diagram schematically showing the structure of a Mach-Zehnder interferometer M. In FIG. **3**, the Mach-Zehnder interferometer M is disposed with two optical waveguides WG_1 and WG_2. In the optical waveguide WG_1, there are disposed an input port IN_1 and an output port OUT_1. Similarly, in the optical waveguide WG_2, there are disposed an input port IN_2 and an output port OUT_2.

Additionally, on the side of the input ports IN_1 and IN_2, the optical waveguides WG_1 and WG_2 are arranged in parallel so as to be capable of optical coupling, and a directional coupler HK_1 is formed. Similarly, on the side of the output ports OUT_1 and OUT_2, the optical waveguides WG_1 and WG_2 are arranged in parallel so as to be capable of optical coupling, and a directional coupler HK_2 is formed.

Between these directional couplers HK_1 and HK_2, there is formed a bend waveguide section C that serves as a combination region of a bend region where the optical waveguides WG_1 and WG_2 are curved and a straight region.

Here, ΔL represents the optical path difference in-the bend waveguide section C of the Mach-Zehnder interferometer M. This ΔL is given by (optical path length of optical waveguide WG_1)−(optical path length of optical waveguide WG_2). Further, light L whose wavelength in a vacuum is λ is input from the input port IN_1.

At this time, “outputted in a bar state” means that, in the directional couplers HK_1 and HK_2, the light L is outputted from the output port OUT_1 of the optical waveguide WG_1 without power transition of the light L to the optical waveguide WG_2 occurring.

Further, “outputted in a cross state” means that, in the directional couplers HK_1 and HK_2, the power of the light L transitions to the optical waveguide WG_2 and the light L is outputted from the output port OUT_2 of the optical waveguide WG_2.

It is known that whether the light L becomes a bar state or a cross state is determined by the relationship between the optical path difference ΔL in the bend waveguide section C and the wavelength λ of the light. That is, when the following expression (2) is satisfied, the light L becomes a cross state, and when the following expression (3) is satisfied, the light L becomes a bar state.

$$2\pi n\Delta L/\lambda=2m\pi \qquad (2)$$

$$2\pi n\Delta L/\lambda=(2m+1)\pi \qquad (3)$$

Here, n is the refractive index of the optical waveguides WG_1 and WG_2. Further, m is a natural number.

Returning again to FIG. **1**A, description will be performed regarding the optical path difference ΔL in the optical multiplexing/demultiplexing device **10**. The optical multiplexing/demultiplexing device **10** performs multiplexing/demultiplexing of light utilizing the aforementioned property of a Mach-Zehnder interferometer.

That is, as shown in FIG. **1**A, the optical path difference ΔL in the bend waveguide sections **18***b* to **24***b* is set such that a first light L_1 is outputted in a bar state and such that a second light L_2 is outputted in a cross state. Thus, the optical multiplexing/demultiplexing device **10** becomes capable of performing multiplexing/demultiplexing of the first light L_1 and the second light L_2.

Next, a method of designing the optical path difference in the bend waveguide sections **18***b* to **24***b* will be described listing actual numerical values.

Here, it will be assumed that the first light L_1 and the second light L_2 are lights of wavelengths that are usually used in an optical subscriber loop system. That is, it will be assumed that a wavelength λ_{1V} of the first light L_1 in a vacuum is 1.3 μm and that a wavelength λ_{2V} of the second light L_2 in a vacuum is 1.49 μm.

Further, n_1 (=2.53) represents the equivalent refractive index of the first and second optical waveguides **14** and **16** regarding the first light L_1, and n_2 (=2.25) represents the equivalent refractive index of the first and second optical waveguides **14** and. **16** regarding the second light L_2.

When these values are assigned to expression (2) and expression (3) while keeping in mind that the first light L_1 is outputted in a bar state and that the second light L_2 is outputted in a cross state, the following expression (4) and expression (5) are respectively obtained.

$$2\pi n_2\Delta L/\lambda_{2V}=2\pi\Delta L/\lambda_2=2\pi\times 2.25\,\Delta L/1.49=2\pi m \qquad (4)$$

$$2\pi n_1\Delta L/\lambda_{1V}=2\pi\Delta L/\lambda_1=2\pi\times 2.53\,\Delta L/1.3=(2m+1)\pi \qquad (5)$$

Here, λ_1 represents the wavelength of the first light L_1 in propagation through the first and second optical waveguides **14** and **16**. Similarly, λ_2 represents the wavelength of the second light L_2 in propagation through the first and second optical waveguides **14** and **16**.

When the difference between expression (4) and expression (5) is calculated, ΔL=1.15 μm is obtained.

When ΔL (=1.15) that has been determined in this manner is assigned to expression (4) to determine m, m=1.729. Incidentally, m has the condition that it is a natural number, and when this condition is not satisfied, the second light L_2 does not become a cross state. It is also possible to make m=2 precisely by the design of the waveguides, but in usual design, the value of m is made into 2, which is the closest natural number to 1.729 (m=2).

Because the value of m is determined by this, when m=2 is again assigned to expression (4) to determine ΔL, ΔL=1.32 μm. This is the final result.

In other words, by making the optical path difference ΔL in the bend waveguide sections **18***b* to **24***b* in the Mach-Zehnder interferometers **18** to **24** equal to 1.32 μm, the first light L_1 can be outputted in a bar state and the second light L_2 can be outputted in a cross state. Thus, wavelength division of the first light L_1 and the second light L_2 becomes possible.

(Regarding ΔL in the Case of a Si-Wire Waveguide)

In the section “(Regarding ΔL)”, the most common case has been described regarding the method of calculating ΔL. However, in a case where the wavelength dispersion of the refractive index of the material that configures the optical waveguides WG_1 and WG_2 is large, it is possible to simultaneously establish the aforementioned expression (2) and expression (3) by optimizing the dimensions of the optical waveguides WG_1 and WG_2.

Here, as a material where the wavelength dispersion of the refractive index of the material that configures the optical waveguides WG_1 and WG_2 is large, for example, Si can be listed.

This point will be described in detail below.

As shown in FIG. **1**A, ΔL is set such that the first light L_1 (wavelength λ_{1V}=1.3 μm) is outputted in a bar state and such that the second light L_2 (wavelength λ_{2V}=1.49 μm) is outputted in a cross state. Consequently, the aforementioned expression (2) and expression (3) can be written as the following expression (2)' and (3)'.

$$2\pi n_1 \Delta L/\lambda_{1V}=2m\pi \qquad (2)'$$

$$2\pi n_2 \Delta L/\lambda_{2V}=(2m+1)\pi \qquad (3)'$$

Here, n_1 is the equivalent refractive index of an optical waveguide that the light of the wavelength λ_{1V} experiences, and n_2 is the equivalent refractive index of an optical waveguide that the light of the wavelength λ_{2V} experiences.

When ΔL that simultaneously satisfies expression (2)' and expression (3)' can be determined, the first light L_1 can be outputted in a bar state and the second light L_2 can be outputted in a cross state.

For that reason, $\Delta n=n_2-n_1$ and $\Delta\lambda=\lambda_{2V}-\lambda_{1V}$ are substituted and these Δn and Δλ are used to determine ΔL. First, when the difference between expression (2)' and expression (3)' is calculated and transformed, the following expression (14) is obtained.

$$2\Delta L=\lambda_{2V}(\lambda_{2V}-\Delta\lambda)/(\Delta\lambda n_2+\lambda_{2V}\Delta n) \qquad (14)$$

In expression (14), the wavelength λ_{2V} is made into a reference wavelength λ_a that is to be emphasized in terms of design, and n_a (=n_2) represents the equivalent refractive index of an optical waveguide that the light of the reference wavelength λ_a experiences. Then, when expression (14) is assigned to expression (2)' and transformed, the following expression (15) is obtained.

$$\Delta n/n_a=(1-\Delta\lambda/\lambda_a)/(2m)-\Delta\lambda/\lambda_a \qquad (15)$$

From expression (15), it will be understood that the design condition of ΔL is determined by the ratios $\Delta n/n_a$ and $\Delta\lambda/\lambda_a$. In other words, it suffices to find the integer m such that expression (15) is satisfied.

Incidentally, in expression (15), Δλ and λ_a become constants in a case where the wavelengths of the first light L_1 and the second light L_2 are already known. Thus, the only unknown amount in expression (15) is $\Delta n/n_a$.

Δn and n_a can be determined from a simulation. FIG. **10** shows this simulation result. In FIG. **10**, the left vertical axis represents the equivalent refractive index n_a (non-dimensional) of an optical waveguide that the light of the reference wavelength λ_a experiences. The right vertical axis represents Δn (non-dimensional). The horizontal axis represents the dimension (μm) of an optical waveguide cut in a plane orthogonal to the light propagation direction. It will be noted that, in this simulation, the cross-sectional shape of the optical waveguide orthogonal to the light propagation direction is square.

This simulation is one where the dimension of the optical waveguide was changed and where the equivalent refractive index n_a of the optical waveguide that the light of the reference wavelength λ_a (=1.49 μm) experiences and Δn_a were calculated. From the result shown in FIG. **10**, $\Delta n/n_a$ can be determined.

FIG. **11** is a characteristic diagram where expression (15) is graphed. In FIG. **11**, the vertical axis is $\Delta n/n_a$ (non-dimensional), and the horizontal axis is the dimension of the optical waveguide. In FIG. **11** also, similar to FIG. **10**, the cross-sectional shape of the optical waveguide is square.

In FIG. **11**, three horizontal lines are shown, and these are values of $\Delta n/n_a$ that are obtained by respectively assigning the values of m=1, 2, 3 to expression (15). Further, the curve in FIG. **11** is values of $\Delta n/n_a$ that are obtained from FIG. **10**.

Referring to FIG. **11**, the horizontal line of m=2 and the curve of $\Delta n/n_a$ that is obtained from FIG. **10** intersect at the point where the dimension of the optical waveguide is about 0.35 μm and where $\Delta n/n_a$ is about 0.09. In other words, it will be understood that expression (15) is satisfied at this point.

Incidentally, when expression (14) is transformed, the following expression (16) is obtained.

$$2n_a\Delta L/\lambda_a=2m=(1-\Delta\lambda/\lambda_a)/(\Delta\lambda/\lambda_a+\Delta n/n_a) \qquad (16)$$

Thus, ΔL that can simultaneously satisfy expression (2)' and expression (3)' can be determined by assigning $\Delta n/n_a$ (=0.09) that has been obtained from FIG. **11** to expression (16) together with other known amounts. When calculation is actually performed using expression (16), ΔL=1.17 μm is obtained.

In this manner, in a case where the wavelength dispersion of the refractive index of the material that configures the optical waveguides WG_1 and WG_2 is large, such as in the case of a Si-wire optical waveguide, ΔL that strictly satisfies expression (2) and expression (3) can be determined.

It will be noted that the above argument can also be applied to an optical multiplexing/demultiplexing device that performs multiplexing/demultiplexing of light of N wavelengths (where N is an integer equal to or greater than 3). Here, "multiplexing/demultiplexing light of N wavelengths" means outputting light of (N−i) wavelength (where i is an integer such that $1 \leqq i \leqq N-1$) in a cross state and outputting light of i wavelength in a bar state.

In this case, at both ends of the optical multiplexing/demultiplexing device, the difference in the order of interference of the wavelengths becomes larger than 1. Thus, in this case, expression (2)' and expression (3)' can be written in a more common way as in the following expression (17).

$$2\pi n_j\Delta L/\lambda_j=2\pi(m+\Delta m) \qquad (17)$$

Here, λ_j represents the wavelength of light that is to be multiplexed/demultiplexed and is arranged such that the wavelength becomes shorter the larger that j is (where j is an integer such that $1 \leqq j \leqq N$). Further, n_j is the equivalent refractive index of an optical waveguide that the light whose wavelength is λ_j experiences. Δm is a value that is given by 2−N.

When calculation is performed using expression (17), the aforementioned expression (15) and expression (16) can be respectively transformed into the following expression (15)' and expression (16)' in the case of N wavelengths.

$$\Delta n/n_a=\Delta m(1-\Delta\lambda/\lambda_a)/(2m)-\Delta\lambda/\lambda_a \qquad (15)'$$

$$2n_a\Delta L/\lambda_a=2m=\Delta m(1-\Delta\lambda/\lambda_a)/(\Delta\lambda/\lambda_a+\Delta n/n_a) \qquad (16)'$$

Thus, by the same argument as mentioned above, the value of ΔL that enables the multiplexing/demultiplexing of light of N wavelengths can be determined from expression (15)' and expression (16)' in a case where the wavelength dispersion of the refractive index of the material that configures the optical waveguides WG_1 and WG_2 is large.

(Design of the Bend Waveguides that Achieves ΔL)

Referring to FIG. **4**A, a method of designing the first and second optical waveguides **14** and **16** for achieving the aforementioned optical path difference ΔL in the bend waveguide sections **18**_b_ to **24**_b_ will be described. FIG. **4**A is-an enlarged plan diagram of relevant portions of a bend waveguide section. It will be noted that, because the shapes of the bend waveguide sections **18**_b_ to **24**_b_ are the same, in the following description, description will be performed using the bend waveguide section **22**_b_ as an example.

The bend waveguide section **22**_b_ is designed connecting straight waveguides, that is, straight regions, and curve waveguides, that is, bend regions, that have uniform radii of curvature.

That is, as shown in FIG. **4**, the first optical waveguide **14** in the bend waveguide section **22**_b_ is configured in the order of a curve waveguide **50**_a_, a curve waveguide **50**_b_, a straight waveguide **50**_c_, a curve waveguide **50**_d_ and a curve waveguide **50**_e_ from the side of the first optical input/output port **14**_a_.

Here, in the curve waveguides **50**_a_, **50**_b_, **50**_d_ and **50**_e_, a radius of curvature R and an arc slope angle θ are equal. Further, the length of the straight waveguide **50**_c_ is geometrically determined as $\Delta L \cos \theta/(1-\cos \theta)$ using the arc slope angle θ and the optical path difference ΔL between the first and second optical waveguides **14** and **16** in the bend waveguide section **22**_b_.

Similarly, the second optical waveguide **16** in the bend waveguide section **22**_b_ is configured in the order of a curve waveguide **51**_a_, a straight waveguide **51**_b_, a curve waveguide **51**_c_, a straight waveguide **51**_d_ and a curve waveguide **51**_e_ from the side of the first optical input/output port **16**_a_.

Here, in the curve waveguides **51**_a_ and **51**_e_, the radius of curvature R and the arc slope angle θ are equal. Further, the radius of curvature of the curve waveguide **51**_c_ is R and the arc slope angle is 2θ. It will be noted that R and θ in the aforementioned first optical waveguide **14** and R and θ in the second optical waveguide **16** are respectively the same values.

Further, the lengths of the straight waveguides **51**_b_ and **51**_d_ are geometrically determined as $(\Delta L/2)/(1-\cos \theta)$ using the arc slope angle θ and the optical path difference ΔL between the first and second optical waveguides **14** and **16** in the bend waveguide section **22**_b_.

In order to determine R and θ in the bend waveguide section **22**_b_ of this structure, there will be considered a condition where intensity loss of light that propagates through the bend waveguide section **22**_b_ becomes a minimum.

Here, α_R represents intensity loss of light per unit length in the curve waveguides **50**_a_, **50**_b_, **50**_d_, **50**_e_, **51**_a_, **51**_c_ and **51**_e_. Further, α_S represents intensity loss of light per unit length of the straight waveguides **50**_c_, **51**_b_ and **51**_d_.

Moreover, α_{JRS} represents intensity loss of light at the joint portion between the curve waveguide **50**_b_ and the straight waveguide **50**_c_, the joint portion between the straight waveguide **50**_c_ and the curve waveguide **50**_d_, the joint portion between the curve waveguide **51**_a_ and the straight waveguide **51**_b_, the joint portion between the straight waveguide **51**_b_ and the curve waveguide **51**_c_, the joint portion between the curve waveguide **51**_c_ and the straight waveguide **51**_d_, and the joint portion between the straight waveguide **51**_d_ and the curve waveguide **51**_e_.

Further, α_{JRR} represents intensity loss of light at the joint portion between the curve waveguides **50**_a_ and **50**_b_ and the joint portion between the curve waveguides **50**_d_ and **50**_e_.

At this time, a sum $\alpha_{14}L_{14}$ of intensity loss of light of the first optical waveguide **14** in the bend waveguide section **22**_b_ is given by the following expression (6). It will be noted that, here, L_{14} represents the total length of the first optical waveguide **14** in the bend waveguide section **22**_b_, and α_{14} represents intensity loss per unit length of the first optical waveguide **14** in the bend waveguide section **22**_b_.

$$\alpha_{14}L_{14}=\alpha_R 4R\theta+(\alpha_S \Delta L \cos \theta)/(1-\cos \theta)+2\alpha_{JRS}+2\alpha_{JRR} \quad (6)$$

Further, a sum $\alpha_{16}L_{16}$ of intensity loss of light of the second optical waveguide **16** in the bend waveguide section **22**_b_ is given by the following expression (7). It will be noted that, here, L_{16} represents the total length of the second optical waveguide **16** in the bend waveguide section **22**_b_, and α_{16} represents intensity loss per unit length of the second optical waveguide **16** in the bend waveguide section **22**_b_.

$$\alpha_{16}L_{16}=\alpha_R 4R\theta+(\alpha_S \Delta L)/(1-\cos \theta)+4\alpha_{JRS} \quad (7)$$

It is known that, usually, intensity loss of light in the curve waveguides **50**_a_, **50**_b_, **50**_d_, **50**_e_, **51**_a_, **51**_c_ and **51**_e_ becomes larger the smaller that the radius of curvature R becomes. Consequently, from expression (6) and expression (7), it is suggested that there exists θ where intensity loss of light becomes a minimum.

Thus, in the bend waveguide section **22**_b_, a condition that minimizes intensity loss of light regarding the second optical waveguide **16** is determined from expression (7). It will be noted that the reason that the condition of minimizing intensity loss of light is determined regarding the second optical waveguide **16** rather than the first optical waveguide **14** is because the optical path length of the second optical waveguide **16** is longer than the optical path length of the first optical waveguide **14** and, consequently, intensity loss of light is larger in the second optical waveguide **16** than in the first optical waveguide **14**.

That is, the following expression (8) is obtained as a conditional expression that minimizes intensity loss of light by differentiating expression (7) by θ.

$$d(\alpha_{16}L_{16})/d(\theta)=\alpha_R 4R-(\alpha_S \Delta L \sin \theta)/(1-\cos \theta)^2=0 \quad (8)$$

When expression (8) is transformed, the following expression (9) is obtained.

$$R/\Delta L=(\alpha_S/\alpha_R)\times\sin \theta/\{4(1-\cos \theta)^2\} \quad (9)$$

As will be understood from expression (9), the condition that minimizes intensity loss of light becomes a relationship between θ and a standardized radius of curvature $R/\Delta L$.

FIG. **5** shows, regarding a case where $\alpha_S/\alpha_R=1$, the relationship (curve **1**) between θ and $R/\Delta L$ of expression (9) and the relationship (curve **2**) between θ and the total length $L_{16}/\Delta L$ of the standardized second optical waveguide **16** that has been determined assigning the value of $R/\Delta L$ that has been obtained from this relationship to expression (7).

In FIG. **5**, the left vertical axis represents $R/\Delta L$ (non-dimensional), and the right vertical axis represents $L_{16}/\Delta L$ (non-dimensional). The horizontal axis represents θ (degrees).

Incidentally, as is conventionally known, a practical radius of curvature R, where intensity loss α_R of light per unit length in a curve waveguide and intensity loss α_S of light per unit length in a straight waveguide become substantially equal, is equal to or greater than 5 μm.

Thus, when $R/\Delta L$ is determined using 5 μm as R and using ΔL (=1.32 μm) that has been determined in the section "(Regarding ΔL)" and this is applied to curve **1** of FIG. **5**, θ that can minimize intensity loss $\alpha_{16}L_{16}$ of light is determined to be about 30°.

Further, when $\theta=30°$ and $\Delta L=1.32$ μm are applied to curve **2** of FIG. **5**, the total length L_{16} of the second waveguide **16** that minimizes intensity loss $\alpha_{16}L_{16}$ of light is determined to be about 26 μm.

In order words, even when the lengths of the directional coupler sections **18***a* to **24***a* are taken into consideration, the total length of the optical multiplexing/demultiplexing device **10** can be controlled to about 200 μm.

(Regarding the Widths of the Optical Waveguides in the Directional Coupler Sections and the Bend Waveguide Sections)

In the section "(Structure of the Mach-Zehnder Interferometers)", the width W**2** of the optical waveguides in the directional coupler sections **18***a* to **24***a* was described as being slightly smaller than the width W**1** of the optical waveguides in the bend waveguide sections **18***b* to **24***b*. The reason for this is to make the optical multiplexing/demultiplexing device **10** polarization-independent.

It is known that, in order to ensure that polarization dependence does not arise in the bend waveguide sections **18***b* to **24***b* that are configured as channel type waveguides, it is good for the transverse cross-sectional shapes (shapes of cut surface perpendicular to the light propagation. direction) of the first and second optical waveguides **14** and **16** to be square.

Based on this, the transverse cross-sectional shapes of the first and second optical waveguides **14** and **16** that configure the bend waveguide sections **18***b* to **24***b* are made into squares of, preferably for example, 0.3 μm×0.3 μm.

By designing the dimension of the transverse cross-sectional shapes of the bend waveguide sections **18***b* to **24***b* in this manner, in the bend waveguide sections **18***b* to **24***b*, the first and second optical waveguides **14** and **16** become polarization-independent and function as single mode waveguides with respect to the first light L_1 and the second light L_2.

In order to make the directional coupler sections **18***a* to **24***a* polarization-independent, it is necessary to adjust the transverse cross-sectional shapes of the first and second optical waveguides **14** and **16** and the coupling lengths (lengths along the light propagation direction) of the directional coupler sections **18***a* to **24***a*.

More specifically, the inventors performed a simulation changing the coupling lengths and the widths of the first and second optical waveguides **14** and **16** regarding the second light L_2 of the wavelength λ_{2V} (=1.49 μm) and determined a coupling length and a waveguide width where the directional coupler sections **18**a to **24***a* become polarization-independent.

FIG. **6**A and FIG. **6**B show that simulation result. In both FIG. **6**A and FIG. **6**B, the vertical axis represents the coupling length (μm) and the horizontal axis represents the width (μm) of the first and second optical waveguides **14** and **16**.

Further, FIG. **6**A shows a case where the gap between the first and second optical waveguides **14** and **16** is 0.3 μm, and FIG. **6**B shows a case where the gap between the first-and second optical waveguides **14** and **16** is 0.35 μm.

Further, in FIG. **6**A and FIG. **6**B, curve **1** indicated by the solid line represents the relationship between waveguide width and coupling length relating to TE polarization, and curve **2** indicated by the chain line represents the relationship between waveguide width and coupling length relating to TM polarization.

It will be noted that, in both FIG. **6**A and FIG. **6**B, the simulation was performed with a height H of the first and second optical waveguides **14** and **16** being, similar to the bend waveguide sections **18***b* to **24***b*, 0.3 μm.

Referring to FIG. **6**A, it will be understood that, in the directional coupler sections **18***a* to **24***a*, when the gap between the first and second optical waveguides **14** and **16** is 0.3 μm, curves **1** and **2** intersect at the point where the coupling length (vertical axis) is about 13 μm and where the waveguide width (horizontal axis) is about 0.28 μm.

Further, referring to FIG. **6**B, it will be understood that, in the directional coupler sections **18***a* to **24***a*, when the gap between the first and second optical waveguides **14** and **16** is 0.35 μm, curves **1** and **2** intersect at the point where the coupling length (vertical axis) is about 21 μm and where the waveguide width (horizontal axis) is about 0.287 μm.

This means that the directional coupler sections **18***a* to **24***a* become polarization-independent at these points of intersection between curve **1** and curve **2**. However, when FIG. **6**A and FIG. **6**B are compared with each other, it will be understood that polarization dependence is smaller when the gap between the first and second optical waveguides **14** and **16** is 0.3 μm than when the gap between the first and second optical waveguides **14** and **16** is 0.35 μm because the inclinations of both curve **1** and curve **2** are more gradual in FIG. **6**A than in FIG. **6**B.

Thus, when dimensional error at the time of manufacture of the directional coupler sections **18***a* to **24***a* is taken into consideration, even when the dimension is off somewhat, FIG. **6**A, where there is little shift from the optimum condition (where the gap is 0.3 μm), is more advantageous in terms of design.

It will be noted that the reason that design of the directional coupler sections **18***a* to **24***a* was performed focusing on the second light L_2 of the wavelength λ_{2V} in this simulation will be described below.

When the first and second optical waveguides **14** and **16** are formed by single crystal silicon, in comparison to when they are formed by quartz, in the wavelength range (1.3 to 1.49 μm) used in an ONU, the wavelength dependence of the directional coupler sections **18***a* to **24***a* is large, and a difference of about 4 times arises in the coupling length. In other words, coupling is extremely weak in the first light L_1 of the wavelength λ_{1V} (1.3 μm) in comparison to the second light L_2 of the wavelength λ_{2V} (1.49 μm).

Thus, it is advantageous in terms of design for the first light L_1, whose coupling is weak, to be outputted in a bar state. When designed in this manner, it is necessary for the second light L_2 to be outputted in a cross state. Incidentally, it is known that, usually, in a Mach-Zehnder interferometer, it is necessary to strictly design the coupling length in order to output a cross state with a good extinction ratio. On the other hand, it is known that a bar state is outputted with a good extinction ratio even when the coupling length is not strictly designed.

This is the reason why design of the directional coupler sections **18***a* to **24***a* was performed only in regard to the second light L_2.

(Operation)

Referring again to FIG. **1**A, operation of the optical multiplexing/demultiplexing device **10** of this exemplary embodiment will be described.

First, a case will be considered where the first light L_1 (wavelength λ_{1V}=1.3 μm) and the second light L_2 (wavelength λ_{2V}=1.49 μm) are input to the optical multiplexing/demultiplexing device **10** from the first optical input/output port **14***a*.

In this case, the first light L_1 is outputted in a bar state, that is, from the second optical input/output port **14***b*. On the other hand, the second light L_2 is, as mentioned above, outputted in a cross state, that is, from the second optical input/output port **16***b*.

In a case where the optical multiplexing/demultiplexing device **10** is used as an ONU, the first light L_1 is an uplink signal from the subscriber loop to the station and the second light L_2 is a downlink signal from the station to the subscriber loop.

In this case, the first light L_1 (uplink signal) that has been input from the second optical input/output port **14***b* is outputted from the first optical input/output port **14***a* in a bar state. Further, the second light L_2 (downlink signal) that has been input from the first optical input/output port **14***a* is outputted from the second optical input/output port **16***b* in a cross state.

Next, referring to FIG. **7**, operating characteristics of the optical multiplexing/demultiplexing device **10** of this exemplary embodiment will be described. FIG. **7** is a simulation result of the operating characteristics. The vertical axis represents the ratio (non-dimensional) of output intensity with respect to input intensity of the bar state and the cross state, and the horizontal axis represents the wavelength of light that has been input to the optical multiplexing/demultiplexing device **10**. Further, in FIG. **7**, curve **1** indicated by the solid line represents the bar state, and curve **2** indicated by the chain line indicates the cross state.

The optical multiplexing/demultiplexing device **10** that was used in the simulation was, except for the following points, designed with the dimensions that have been described in the sections "(Structure)" to "(Regarding the Widths of the Optical Waveguides in the Directional Coupler Sections and the Bend Waveguide Sections)".

(1) Micro-adjustment of Coupling Length of Directional Coupler Sections **18***a* to **24***a*

In the vicinities of the joint portions between the directional coupler sections **18***a* to **24***a* and the bend waveguide sections **18***b* to **24***b*, the first and second optical waveguides **14** and **16** that configure the bend waveguides **18***b* to **24***b* end up approaching each other as far as a distance where they are capable of optical coupling. For that reason, the coupling length of the directional coupler sections **18***a* to **24***a* was adjusted to a short 11.6 μm.

(2) The optical path difference ΔL between the first and second optical waveguides **14** and **16** in the bend waveguide sections **18***b* to **24***b* was made into 1.344 μm.

This is because, taking into consideration the, equivalent refractive index of the first and second optical waveguides **14** and **16** that are made of single crystal silicon, the optical path difference ΔL was adjusted such that the first light L_1 (wavelength λ_{1V}=1.3 μm) and the second light L_2 (wavelength λ_{2V}=1.49 μm) respectively become center wavelengths in the bar state and the cross state.

Referring to FIG. **7**, it will be understood that, in both the bar state in the vicinity of wavelength 1.3 μm and the cross state in the vicinity of 1.49 μm, wavelength division is performed in a broad wavelength range. The wavelength band for which wavelength division is completely performed is about 50 nm, and it is possible to completely absorb wavelength fluctuation of the light source and manufacturing error of the optical multiplexing/demultiplexing device **10**.

Further, output light of an intensity that is substantially equal to the intensity of the input light can be obtained.

(Effects)

(1) The optical multiplexing/demultiplexing device **10** of this exemplary embodiment can, as shown in FIG. **7**, perform multiplexing/demultiplexing of the first light L_1 and the second light L_2 virtually without causing crosstalk.

(2) Further, as shown in FIG. **7**, the optical multiplexing/demultiplexing device **10** of this exemplary embodiment can reduce loss of light intensity in comparison to convention.

(3) Further, the optical multiplexing/demultiplexing device **10** has a total length of about 200 μm and is compact in comparison to a conventional Si-made Mach-Zehnder type of ONU.

(Design Conditions, Modifications, Etc.)

(1) In this exemplary embodiment, a case has been described where the four Mach-Zehnder interferometers **18** to **24** were connected in series. However, the number of the Mach-Zehnder interferometers that configure the optical multiplexing/demultiplexing device **10** is not limited to four.

As long as the optical multiplexing-demultiplexing device **10** is disposed with one or more each of the bar state pair and the cross state pair, there is no limitation on the number of those Mach-Zehnder interferometers. For example, as shown in FIG. **8**A, the number of the Mach-Zehnder interferometers may also be three. In this case, one each of the bar state pair and the cross state pair are disposed.

Further, as shown in FIG. **8**B, the number of the Mach-Zehnder interferometers may also be six. In this case, three of the bar state pairs and two of the cross state pairs are disposed.

(2) In this exemplary embodiment, a case has been described where, at the boundary portions between the bend waveguide sections **18***b* to **24***b* and the directional coupler sections **18***a* to **24***a*, the widths of the first and second optical waveguides **14** and **16**,were changed discontinuously from **W1** to **W2**. In this design also, intensity loss of light can be controlled at a practically sufficient level. However, in order to reduce intensity loss of loss even more, it is preferred that the widths of the first and second optical waveguides **14** and **16** are changed smoothly in a tapered manner at the boundary portions.

(3) As described in the section "(Design of the Bend Waveguides that Achieves ΔL)", in this exemplary embodiment, the bend waveguide sections **18***b* to **24***b* of the Mach-Zehnder interferometers **18** to **24** were formed by straight waveguides and curve waveguides that have uniform radii of curvature.

However, the bend waveguide sections **18***b* to **24***b* may also be designed combining curve waveguides with different radii of curvature.

More specifically, a bend waveguide section **60***b* of a Mach-Zehnder interferometer **60** that configures the optical multiplexing/demultiplexing device **10** may also be designed as shown in FIG. **9**.

That is, this Mach-Zehnder interferometer **60** is configured by a first optical waveguide **62** and a second optical waveguide **64**. Additionally, directional coupler sections **60***a* and **60***a* and the bend waveguide section **60***b* are formed by these first and second optical waveguides **62** and **64**.

The first optical waveguide **62** in the bend waveguide section **60***b* is configured in the order of a curve waveguide **66***a*, a curve waveguide **66***b*, a curve waveguide **66***c* and a curve waveguide **66***d*.

Here, in the curve waveguides **66***a* to **66***d*, a radius of curvature R_2 and an arc slope angle θ_2 are equal.

The second optical waveguide **64** in the bend waveguide section **60***b* is configured in the order of a curve waveguide **68***a*, a curve waveguide **68***b*, a curve waveguide **68***c* and a curve waveguide **68***d*.

Here, in the curve waveguides **68***a* to **68***d*, a radius of curvature R_1 ($\neq R_2$) and an arc slope angle θ_1 ($\neq \theta_2$) are equal.

In this bend waveguide section **60***b*, the method of designing the first and second optical waveguides **62** and **64** for achieving the optical path difference ΔL conforms to the method that has been described in "(Design of the Bend Waveguides that Achieves ΔL)".

That is, regarding the second optical waveguide **64** whose optical path length is long, intensity loss $\alpha_{64}L_{64}$ of light in the bend waveguide section **60***b* is considered. Here, L_{64} represents the total length of the second optical waveguide **64** in the bend waveguide section **60***b*, and α_{64} represents intensity loss per unit length of the second optical waveguide **64** in the bend waveguide section **60***b*. This intensity loss $\alpha_{64}L_{64}$ is given by the following expression (10).

$$\alpha_{64}L_{64}=\alpha_{R1}4R_1\theta_1=\alpha_{R1}\{\Delta L+4R_2\sin^{-1}(R_1\sin\theta_1/R_2)\}+4\alpha_{JRR} \quad (10)$$

Here, α_{R1} represents intensity loss of light per unit length in the curve waveguide sections **68***a* to **68***d*. Further, α_{JRR} represents intensity loss of light in the joint portion between the curve waveguides **68***a* and **68***b*, the joint portion between the curve waveguides **68***b* and **68***c*, and the joint portion between the curve waveguides **68***c* and **68***d*.

From FIG. **9**, it will be understood that, when R_2 is made infinite, the optical path difference ΔL is efficiently obtained. Thus, in expression (10), by making R_2 infinite, the following expression (11) is obtained.

$$\alpha_{64}L_{64}=\alpha_{R1}(\Delta L+4R_1\sin\theta_1)+4\alpha_{JRR} \quad (11)$$

Incidentally, in the bend waveguide section **60***b*, the lengths at which the first and second optical waveguides **62** and **64** are projected on the central axis of the Mach-Zehnder interferometer must be equal, so the following expression (12) is obtained.

$$R_1=\Delta L/\{4(\theta_1-\sin\theta_1)\} \quad (12)$$

When expression (12) is assigned to expression (11), the following expression (13) is obtained as a final result.

$$\alpha_{64}L_{64}=\alpha_{R1}\Delta L\{\theta_1/(\theta_1-\sin\theta_1)\}+4\alpha_{JRR} \quad (13)$$

From expression (13), it will be understood that the intensity loss $\alpha_{64}L_{64}$ of light changes with respect to the arc slope angle θ_1. Further, it will be understood that it is preferred that the arc slope angle θ_1 is large and that the intensity loss $\alpha_{64}L_{64}$ of light becomes the smallest when $\theta_1=\pi/2$.

What is claimed is:

1. An optical multiplexing/demultiplexing device comprising:

a substrate; and

first and second optical waveguides that are arranged in parallel and formed on the substrate, with one end of each of the first and second optical waveguides being configured as a first optical input/output port and the other end of each of the first and second optical waveguides being configured as a second optical input/output port,

wherein

the first and second optical waveguides between the first and second optical input/output ports include three or more Mach-Zehnder interferometers in series,

multiplexed light comprising at least first light and second light whose wavelengths are different and which is input to either one of the first optical input/output ports is separated by wavelength and outputted from each of the second optical input/output ports of the first and second optical waveguides,

the absolute value of an optical path difference ΔL with respect to light that propagates through the first and second optical waveguides in each of the Mach-Zehnder interferometers is constant, and

the three or more Mach-Zehnder interferometers include at least one pair of successive Mach-Zehnder interferometers where the sum of optical path differences of the two interferometers becomes +2ΔL or −2ΔL and at least one pair of successive Mach-Zehnder interferometers where the sum of optical path differences of the two interferometers becomes 0.

2. The optical multiplexing/demultiplexing device of claim **1**, wherein when λ_1 and λ_2 ($\lambda_2>\lambda_1$) respectively represent the wavelengths of the first light and the second light inside the first and second optical waveguides, the optical path difference ΔL is given by the following expressions

$$\Delta L=(2m+1)\times\lambda_1 \text{ and } \Delta L=2m\times\lambda_2 \text{ (where m is a natural number).}$$

3. The optical multiplexing/demultiplexing device of claim **2**, wherein the first light is outputted in a bar state from one of the second optical input/output ports and the second light is outputted in a cross state from the other of the second optical input/output ports.

4. The optical multiplexing/demultiplexing device of claim **1**, wherein the first and second optical waveguides are formed using Si as a material.

5. The optical multiplexing/demultiplexing device of claim **1**, wherein

cross-sectional shapes, orthogonal to the light propagation direction, of the first and second optical waveguides that form bend waveguide sections of the Mach-Zehnder interferometers are substantially square, and

cross-sectional shapes, orthogonal to the light propagation direction, of the first and second optical waveguides that form directional coupler sections of the Mach-Zehnder interferometers are substantially rectangular where the length in a direction perpendicular to a main surface of the substrate is longer than the length in a direction parallel to the main surface of the substrate.

6. The optical multiplexing/demultiplexing device of claim **5**, wherein the bend waveguide sections are formed by a straight waveguide and by a plurality of curved waveguides whose radii of curvature are equal.

7. The optical multiplexing/demultiplexing device of claim **2**, wherein the optical path difference ΔL is determined utilizing the wavelength dependence of the equivalent refractive index of the material that forms the first and second optical waveguides.

8. The optical multiplexing/demultiplexing device of claim **7**, wherein the material that forms the first and second optical waveguides is Si.

9. The optical multiplexing/demultiplexing device of claim **7**, wherein when Δλ represents the wavelength difference between the first light and the second light, Δn represents the equivalent refractive index difference between the first and second optical waveguides that the first light and the second light experience, and m is a positive integer, the following expression is satisfied

$$\Delta n/n_2=(1-\Delta\lambda/\lambda_2)/(2m)-\Delta\lambda/\lambda_2$$

and the optical path difference ΔL satisfies the following expression

$$2n_2\Delta L/\lambda_2=(1-\Delta\lambda/\lambda_2)/(\Delta\lambda/\lambda_2+\Delta n/n_2)$$

where n_2 is the equivalent refractive index of an optical waveguide that the second light experiences.

10. An optical multiplexing/demultiplexing device comprising:

a substrate; and

first and second optical waveguides that are arranged in parallel and formed on the substrate, with one end of each of the first-and second optical waveguides being configured as a first optical input/output port and the other end of each of the first and second optical waveguides being configured as a second optical input/output port,

wherein

the first and second optical waveguides between the first and second optical input/output ports include three or more Mach-Zehnder interferometers in series,

multiplexed light of N wavelengths (where N is an integer such that $N \geqq 3$) whose wavelengths are different and which is input to either one of the first optical input/output ports is separated by wavelength and outputted as light of (N−i) wavelength (where i is an integer such that $1 \leqq i \leqq N-1$) from the second optical input/output port of the first optical waveguide, and light of i wavelength is outputted from the second optical input/output port of the second optical waveguide,

when m is, an integer equal to or greater than 1, the absolute value of an optical path difference ΔL with respect to light that propagates through the first and second optical waveguides in each of the Mach-Zehnder interferometers is constant,

the three or more Mach-Zehnder interferometers include at least one pair of successive Mach-Zehnder interferometers where the sum of optical path differences of the two interferometers becomes +2ΔL or −2ΔL and at least one pair of successive Mach-Zehnder interferometers where the sum of optical path differences of the two interferometers becomes 0, and

$$\Delta n/n_a = \Delta m(1-\Delta\lambda/\lambda_a)/(2m) - \Delta\lambda/\lambda_a \text{ and}$$

$$2n_a\Delta L/\lambda_a = 2m = \Delta m(1-\Delta\lambda/\lambda_a)/(\Delta\lambda/\lambda_a + \Delta n/n_a)$$

are simultaneously satisfied,

where Δm is an integer that is given by 2−N, λ_a is a reference wavelength, and n_a is the equivalent refractive index of an optical waveguide that light of the reference wavelength experiences.

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